XTerramechanics:
Integrated Simulation of Planetary Surface Missions

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Team Leads:

José Andrade
California Institute of Technology
jandrade@caltech.edu

Randel Lindemann
Jet Propulsion Laboratory
randel.a.lindemann@jpl.nasa.gov

Karl Iagnemma
Massachusetts Institute of Technology
kdi@mit.edu

Deputy Leads:

Brian Trease
Jet Propulsion Laboratory

Ivan Vlahinić
California Institute of Tech

Carmine Senatore
Massachusetts Institute of Tech

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1 Executive Summary

1.1 Why XTerramechanics?

> **KISS Study Motivation**
>
> *Regolith is the 'skin' of a celestial body that encodes its complex geologic processes. Ability to sense or infer the properties of regolith remotely or in-situ provides insight into geologic history.*

Are there contemporary habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to support or sustain life? Are there habitats that have experienced conditions similar to those on Earth when life emerged, an abode of possible life long past. Mars and Europa (Jupiter's icy moon) have been identified as the most relevant and immediate in the quest to answer these questions. Beyond Mars and Europa, every celestial body of interest appears to have its own geologic history and every new discovery accentuates the overall complexity of our solar system. The exploration of Mars and Europa, and others, both remotely and in situ, is a central priority as part of NASA's current and future goals for understanding the building of new worlds, the requirements for planetary habitats, and the workings of the solar system.

Future missions oriented at exploring the celestial bodies will encounter extremely complex and diverse geologic processes, as encapsulated in the surface regolith. Figure 1 shows an artist's rendering of futuristic missions to Mars and Europa, as an example, and highlights some of the envisioned interactions with the local regolith. Other future NASA missions will emphasize in situ exploration in a variety of extreme environments, including the atmospheres of the giant planets, the surfaces and atmospheres of Venus and planetary satellites, and the surfaces and sub-surfaces of small bodies. This transformative planetary science hinges crucially on the ability to remotely sense, land on, traverse, penetrate, sample, process, and eventually return regolith. Regolith is central to planetary science as it is the bio-chemo-physiologically altered geo-material at the surface of a planetary body that encompasses extraterrestrial telluric deposits. Hence, regolith (including soils, rocks, ice) is the 'skin' of a celestial body and encodes all of the chemical and physical processes that have operated close to or on the surface. Knowledge of the properties and related behavior of planetary surface materials is crucial to unraveling planetary evolution, the search for the conditions that foster or have fostered past life, the development of hitherto impossible missions, and the possibility of pre-human expeditions for safety and resource utilization.

> **KISS Study Motivation**
>
> *Future NASA missions will crucially hinge on their ability to remotely sense, land on, traverse, penetrate, sample, process, and eventually return regolith in extreme environments.*

There is orbital and in situ evidence of complex geologic processes taking place in Mars, including impacts, landslides, gully formation, winds. These processes are responsible for transforming the landscape, encoding the evolution of climate change. An important scientific quest is to determine those geologic processes that are responsible for modifying the Martian crust over time. Regolith properties can give important clues as to the nature of these morphological processes. It is now recognized hat the best way to characterize Martian regolith will be to collect and return samples to Earth for analyses. A Martian sample return mission will require key scientific and technological advances to enable surface exploration and the ability for rovers to traverse complex terrain and to collect, handle, curate, analyze, and study Martian regolith.

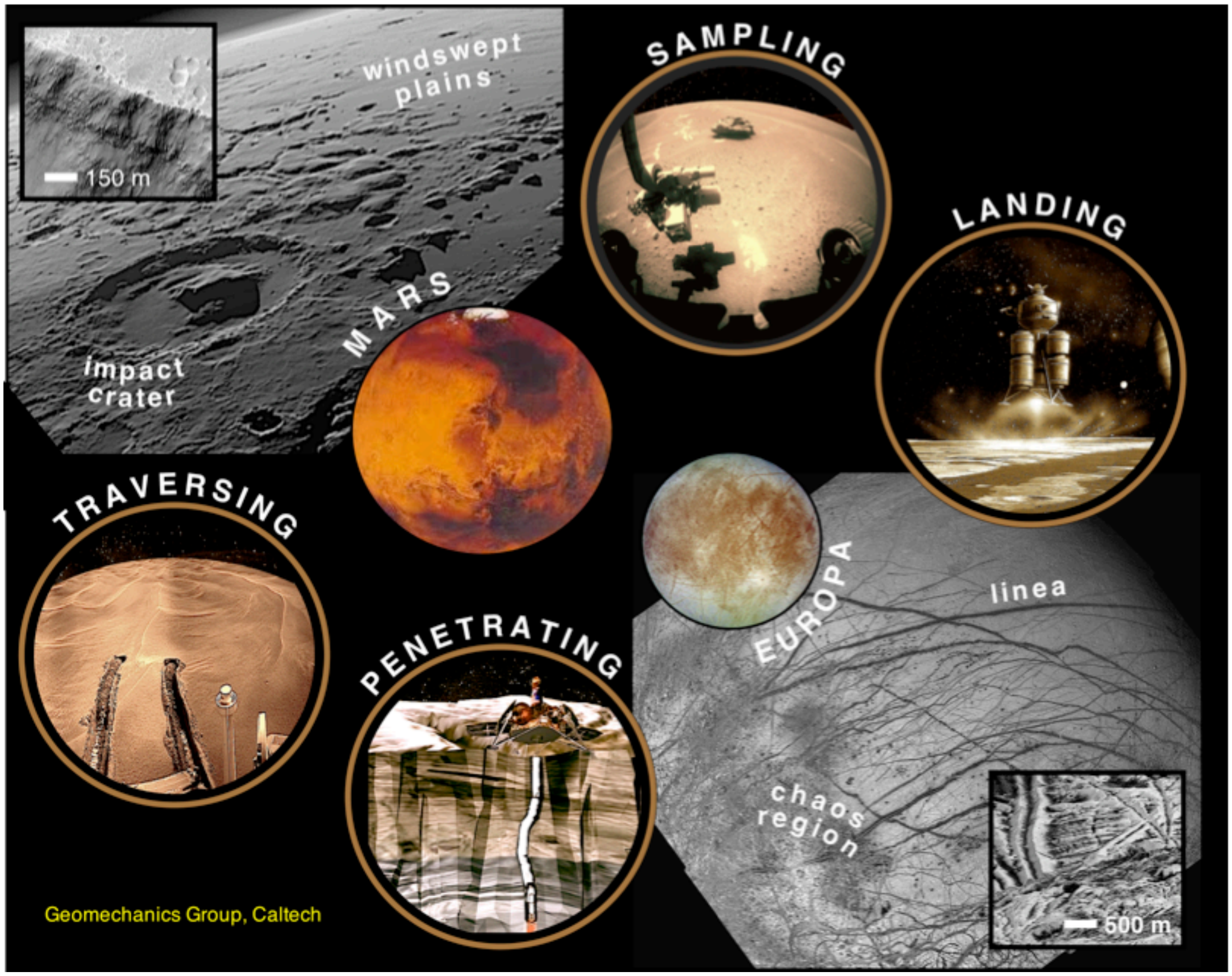


Figure 1: Schematic of hypothetical future missions with Mars and Europa as examples of celestial bodies of interest. Surface topology is shown across scales and potential mission-critical interactions with regolith are highlighted.

Tucked away from Earth, in the outer solar system, the Galilean moon Europa is covered with solid ice displaying mysterious surface features called lineae or cracks, interrupted by spots of random topography dubbed chaos. These striking topological features are believed to be product of probable eruptions of warmer ice as a result of gravitational tides on Europa, eventually resulting on near-surface stresses. Europa is central to the question of habitability within our solar system because of the likely presence of liquid water as part of a large ocean underlying the ice shell. Understanding the mechanics of tectonic patterns (lineae, chaos), their origin, and the interaction between the surface regolith (ice) and the underlying ocean is key to answering some of the pressing science questions related to the Galilean moon. A fundamental understanding of the linkage between the mechanics of the geologic materials and the planetary processes is urgently needed. Furthermore, a future in situ mission to Europa would require enormous science and technology advancements to make possible complex interactions between spacecraft and regolith ranging from landing to sampling to penetrating under very different conditions from those encountered on Earth or Mars.

As exemplified by Mars and Europa, every celestial body of interest has its own geologic history, and coupled to this, its own planetary conditions, such as gravitational field, atmosphere, etc. A lot of this information is encoded in the landscape and composition of the crust. For example, measurements of thermal inertia and albedo are believed to correlate with mechanical properties of the surface regolith, e.g. cohesion. However, this connection remains qualitative and science tools are required to actually quantify this correlation (if it exists). Related to this, it is still unclear how mechanical properties of surface regolith are affected by gravity (or lack thereof). Most models currently used are primitive and extrapolate phenomenology built under full gravity conditions. Current methods for planning, designing, and operating surface missions are underpinned by phenomenological or empirical methods to account for regolith interactions and mechanics. For instance, conclusions made under the Apollo mission may only apply to lunar regolith and not necessarily to those encountered by the Mars Science Laboratory (MSL). Furthermore, the interactions between a landed spacecraft, its components, and regolith on a future mission to Europa, with lower temperatures and thick ice cover, may find little in common with the experience acquired on Mars. Because empirical models permeate the entire lifecycles of missions, the missions become riskier and more expensive.

KISS Study Conclusion*:*

"At present, there is a lack of physical understanding of the fundamental behavior of regolith and its interaction with external stimuli, imposed by landed spacecraft, its tools, and/or penetrating waves."

A danger on relying solely on phenomenological approaches (models) or physical observation also means limited predictive capabilities because the models or observations are only valid within the physical and environmental conditions present in the development of models or physical observation. Physical testing under full gravity (on earth) may not be representative of extraterrestrial conditions. Hence this approach is evolutionary (rather than revolutionary) and expensive. Within the current financial constraints and more advanced computational capabilities, a new paradigm relying on physics rather than evolutionary phenomenology is urgently needed. This KISS study series is motivated by the great need for physics-based models that are predictive under a range of physical conditions, e.g. under full and reduced gravity conditions (planet vs. moon vs. asteroid) or changes in cohesive properties of the regolith (powder vs. sand vs. ice).

KISS Study Conclusion*:*

"A successful research campaign must capture a wide range of physical phenomena: from small-scale granular physics and contact mechanics to large-scale spacecraft dynamics."

1.2 Study finale: Conclusions

The KISS study series was organized around two workshops and one study period, collectively aimed at broadly discussing and brainstorming topics related to the fundamental properties of terrestrial soil and regolith, orbital and in-situ imaging of regolith, and the interactions between spacecraft, its components, and regolith. Interest in this by-invitation-only study series exceeded expectations, with participation and active engagement from students, post-doctoral fellows, faculty, and industry in addition to the core members of the lead team.

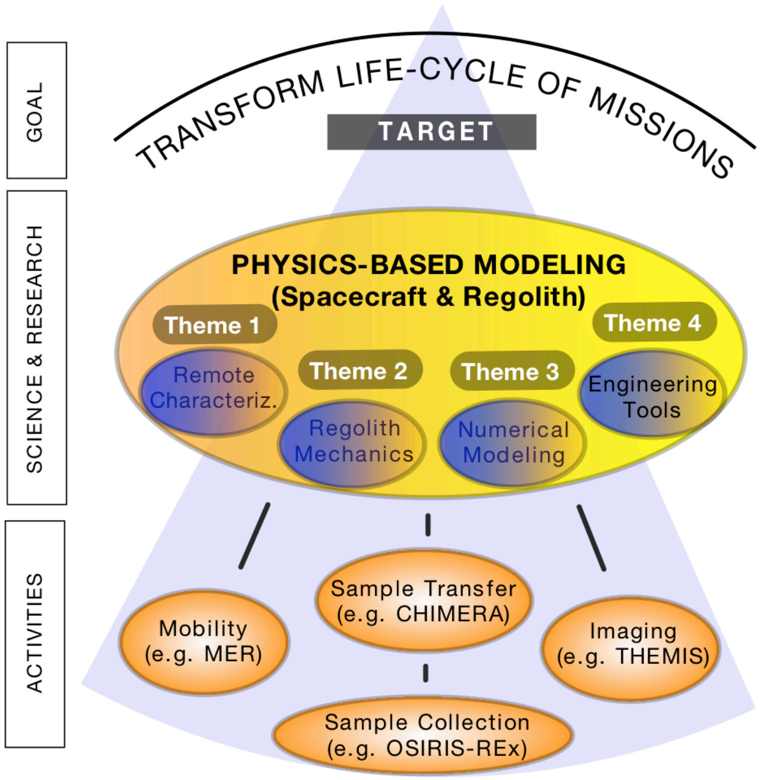


Figure 2: In the course of the KISS study, the participants comprehensively examined many of the mission-critical interactions between the spacecraft and regolith, herein termed activities. Examples of these activities were provided in the context of contemporary NASA missions.

During the study series, research areas critical to the success of future exploration of complex celestial bodies were identified. This was accomplished by comprehensively examining many of the mission-critical interactions between the spacecraft and regolith, termed activities in Figure 2. These include but are not limited to mobility, sample collection, sample transfer, and imaging, with contemporary examples of the role of these activities in active missions providing the context for the discussion. Even when the requirements for many activities are well understood, e.g. distance to traverse to a science destination or volume of material to bring onboard to meet the sampling targets, how to implement these activities in complex environments of diverse celestial bodies continues to be acutely puzzling. The limiting and critical factor in the activities is the following: at present, *there is a lack of physical understanding of the fundamental behavior of regolith and its interaction with external stimuli imposed by landed spacecraft and/or ground penetrating waves.* Only a physics-based modeling paradigm will provide predictive tools toward exploration of environments unlike our own, and in this way transform the life-cycle of future NASA missions.

To reach this goal, a research strategy has been identified - systemically and scientifically examining the underlying complexities of regolith in the context of space missions. The strategy includes characterization and modeling campaigns, to be performed in synergy, as shown in Figure 3. A canonical problem of rover mobility is chosen to showcase the range of scales that a successful campaign must incorporate and a range of physical phenomena that it must capture, from small-scale granular physics and contact mechanics to large-scale spacecraft dynamics. This necessarily means that significant advances in multi-scale and reduced-order methods will need to be made, especially if enhanced insight is to be incorporated as a detection tool or a science tool on board the spacecraft. Gravity, grain size and shape, and grain-scale cohesion were deemed the single most important variables to the overall response of regolith. For example, under reduced gravity and near vacuum, electrostatic cohesive forces may dominate the response of regolith, and lead to unexpected physical properties and geomorphic features. Only a successful physics-based modeling campaign, validated under controlled conditions, would be in position to extrapolate to such environments.

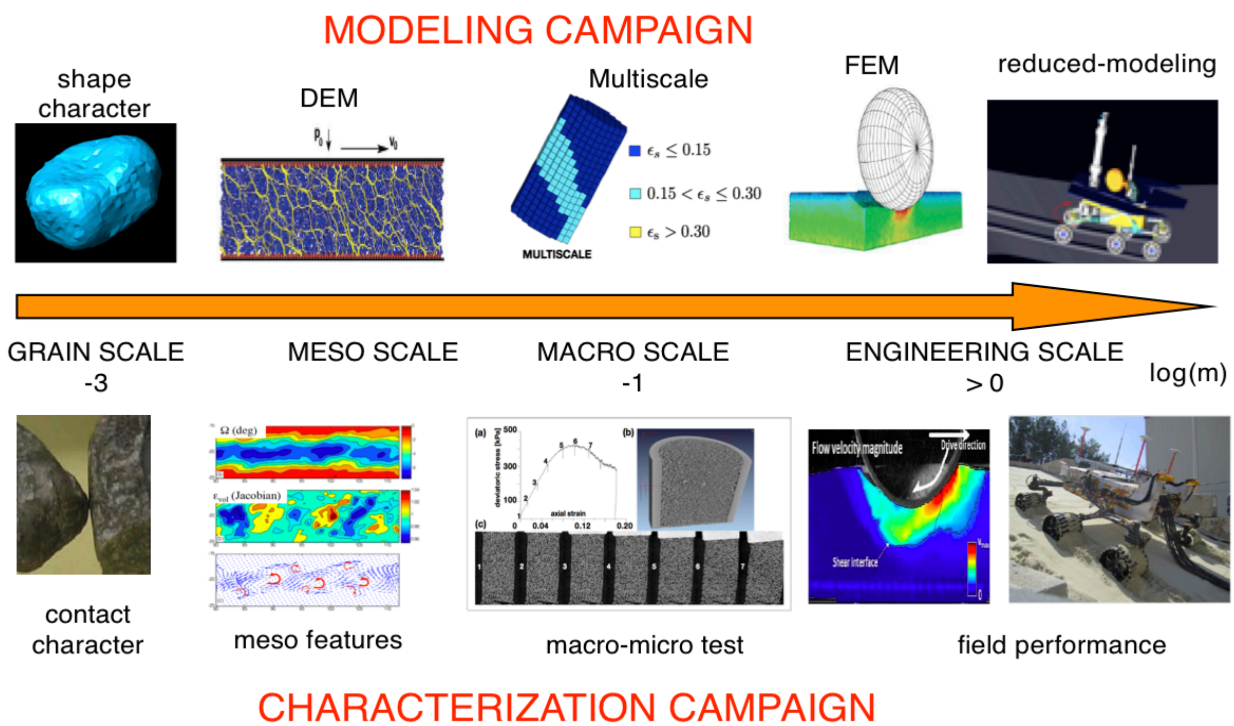


Figure 3: Research strategy identified during the KISS study. We envision a parallel modeling and characterization research campaigns, to systemically and scientifically examine the underlying complexities of regolith in the context of space missions.

We envision that the advancements in physics-based modeling will be made possible by cross-disciplinary developments in Discrete-Element-Modeling (DEM) and nonlinear Finite Element Analysis (FEA) utilizing novel constitutive models of regolith; multi-scale methods seamlessly navigating between DEM and FEA; utilization of enormous increases in computational capability; the development of a range of reduced-order models (e.g. Bekker-Wong models related to rover mobility) that can extract the essential from the more faithful, but also more computationally expensive numerical models. These critical developments to be made are at the intersection of geo and planetary sciences, physics, and mechanics. If achieved, they will result in *more successful and revolutionary types of NASA planetary missions with enhanced science return, and increased return on investment and cost control.*

1.3 Study finale: Remarks

Planets and sub-planets play a host to complex physical and geologic processes. One of the primary ways we gain insight into the nature and history of these processes, and at once begin to answer if these contemporary habitats have or had the ability to support or sustain life, is by exploring the surfaces of these celestial bodies, remotely or in-situ. For example, a remote examination of topography and chemistry of the Mars surface paved way for an MSL landing site, the Gale crater, containing features such as the alluvial fans likely formed by water-carried sediments and steep elevations changes marking sedimentary layers formed during different periods of Mars history.

Revolutionary technologies needed to support future explorations of distant bodies will require robust and versatile tools that are able to interact with regolith. Even current missions (e.g. MSL) continue to face significant challenges in this arena, in the form of successful landing, roving, sampling, and sample transporting of regolith as part of its mission requirements. At minimum, new and innovative experimental campaigns will have to be conducted to ascertain the risks and develop parameters needed for future mission designs involving regolith interactions. This KISS study has enabled us to consider new possibilities in this arena and to think deeply about physics-based solutions in ways that are flexible and open to future science mission requirements. A list of ideas reflecting the content of the workshop discussions is summarized below:

- **Reduced-order models describing spacecraft-regolith interaction are computationally inexpensive, and thus ideal on-board 'instruments' that promise to significantly enhance science return of a mission.** For example, reduced-order mobility models (Section 3.1) can be used for autonomous navigation (e.g. path planning) and self-diagnostics (e.g. incipient embedding detection) leading to increased safety margins. Moreover, because wheel-soil interactions on granular terrain occur at depth (Figure 21), with slip failure initiated within the regolith, mobility response via reduced-order models can be utilized as a science detection tool.
- **Finite elements, and the underlying continuum material models, provide a state of the art platform for predicting systems performance.** Leading industry players**,** such as Caterpillar, provide a success story in the applications of advanced numerical models to solutions of applied engineering problems. Although computationally expensive, FEM tools (Section 3.3) have successfully been used in a wide range of applications, not limited to running gear design, optimization of power requirements related to geomaterial interactions, and integration of instrumented experiments and advanced computational models. With extraterrestrial environments in mind, multi-scale approaches that infuse underlying material physics into the continuum material models stand to take FEM beyond empiricism (Section 3.4).
- **Chemical, mechanical, and physical properties of regolith are closely inter-linked and are at the heart of planetary science.** Properties such as the intrinsic angle of repose (related to inter-particle friction) or dilatancy (related to particle morphology) can be used to reconstruct geologic properties of the surface of celestial bodies. Did wind or a liquid enhance sediment deposition? Do properties of the surface sediment indicate past or present existence of interstitial fluids? These questions, and others, could potentially be inferred from particle morphology or cohesion, properties intimately related to the mechanical behavior of regolith (Section 3.2).

- **At present, tactical and strategic mission execution is often based on subjective human-driven metrics.** Going forward, a transformative challenge will be to turn the subjective metrics, from rover telemetry to power requirements of a sampling arm for instance, into quantitative observations. Any interaction with a celestial body is, de-facto, an in-situ experiment (Section 3.5). Data collected in the course of a landed mission (even data acquired during past missions) is a potential science goldmine. To this end, a full power of computational tools will need to be utilized, including the ability to perform 'back-analysis' of regolith interactions. Related to the previous discussion, visual fine-scale topography as inferred via visual odometry may provide further insight into past or present geologic processes.
- **Microscopic material interactions hold secrets to macroscopic behavior.** The KISS workshops highlighted the extent to which grain-scale processes of regolith are fundamental to its response due to external stimuli. In addition to physical interaction, e.g. landing and penetrating, the stimuli include at-distance sensing, e.g. thermal imaging. A relevant grain scale is clearly material dependent (Section 3.4) and may not be the same both on Europa's icy regolith or martian rippled surface. Can understanding of the processes at different scales paint a better picture of planetary geology? For example, can the expected fine-scale fracture toughness of cold ice play a role in supporting the origins of large-scale ice banding on Europa, and specifically features such as chaos and linea which presumably arose as a result of Europa's tidal flexing (Figure 1).
- **Need for development of faithful regolith simulants.** Terrestrial materials can be synthesized or sourced in order to approximately mimic the expected or measured chemical and mechanical properties of regolith. The physical properties, mineralogy, and particle size distributions need not be identical to regolith, but need to 'faithfully' characterize the desired properties of regolith, e.g. reactivity or compressibility. It is of great need and importance to research and engineering communities, e.g. those wishing to test material handling, transport, and other regolith-related interactions, to develop a physics-based rationale for engineering regolith simulants. At minimum, novel granular materials should be created in order to capture a range of behaviors expected in the context of planetary science (Section 3.6), not limited to extremely rough and angular granular shapes, intensely charged granular surfaces, and expected mineral compositions.
- **Lowering cost of missions and changing the life-cycle design.** The farther the mission, the more critical are the power, weight, and space requirements. Presently, empiricism permeates the lifetime of missions (Section 1.1). Moreover, earth-based testing campaigns are not necessarily representative of the space environments. This is particularly true in the context of regolith where particles are often held together via confinement provided by gravitational weight or via weak inter-particle cohesive forces provided by particle morphology or space charging. Numerical modeling of regolith-related interactions needs to be a significant component of future cost savings, particularly when part of the mission-critical requirements.

2 Components of the Study

2.1 Study organization and goals

The study consisted of roughly two weeklong workshops and one study period, held at the Keck Institute on the 6th floor of the Millikan building. The first workshop began on June 20th and the second workshop closed on August 3rd, 2011. In the interim, a focused study period was held to explore the specific technical ideas brought to light during workshop 1 and to set the stage for deeper discussions in Workshop 2. Overall, there were close to 40 participants (a detailed list is provided in Appendix C), with each person carefully chosen to bring a particular expertise relevant to the overall program. In addition, the list of invitees for Workshop 2 was updated to reflect the study direction following the Workshop 1. Beyond the senior-level academics, JPL/NASA engineers and scientists, and industry leaders, several graduate students and post-doctoral scholars were also actively involved in the KISS study. Post-docs were also integrated into organizational aspects of the study, which proved to be a particularly enjoyable and fruitful decision.

The strategic goal of this KISS study was to facilitate an open forum. With the background of the invitees in mind, the organizers asked all participants to come prepared to deliver a concise lecture on their topic of expertise. In addition to elaborating on previously performed research, the invitees were also asked to delve deeply on the challenges that remain and future direction of their respective fields of study. The benefit was that in addition to getting everyone up to speed on the present technical and scientific state-of-the-art, all participants were also urged to 'think into the future' from the very start.

The morning of the opening workshop began with a series of four presentations, open to public and recorded, on the topic of measurements and models of regolith and regolith-rover interaction in NASA's current Mars Exploration Program (see Figure 5 for a posted flyer). The week continued with an in-depth look into the more salient aspects of regolith-related challenges consisting of: (1) Integrated simulation of planetary surface missions. (2) The basics of soil phenomenology: current modeling and testing tools. (3) The advances in testing and modeling tools: multi-scale and physics-based approaches. (4) Reality on the ground: architecture of mission development, design, and operation. At all times, the context was provided by the experiences of the past and present NASA missions (e.g. Lunar Program, Mars Exploration Program), with an eye toward the future, as exemplified by NASA's pipeline missions (e.g. touch-and-go asteroid sampling), novel mobility design paradigms (e.g. axel rover), and the futuristic (see Section 3.6).

The final workshop was more specific, geared toward establishing detailed research thrusts needed overcome the previously identified gaps. Specifically, the final goal was to identify key areas of research that would produce the highest potential payoff, thereby transforming the life-cycle of future space missions. During the course of the final week, a cutting-edge research campaign was identified (see Figure 3). A more comprehensive picture of the proposed research campaign is provided in the Phase II KISS proposal.

2.2 Building a synergistic community

The KISS workshops served a very important role in bringing together a comprehensive xTerramechanics community that did not exist prior to the workshops. While technical exchange was one focus, considerable time was spent building relationships and understanding the background and research goals of the many individuals that were brought together during the KISS study (see Figure 4). Before the workshops, the organizers were aware of researchers separately studying these elemental topics, but saw that they and their capabilities were islands of geoscience, planetary science, physics and mechanics of regolith, and robotics. The workshop provided a venue to connect and energize this disparate community in an intelligent way, across NASA's research and engineering offices, academic institutions, and industry.

During the workshops, engineers mixed with scientists and young researchers mingled with the leads of their fields, on equal terms during discussions and more informally during the course of lunch and dinner settings. In addition, a digital workspace was provided by an online KISS wiki-site, where participants exchanged papers before the daily meetings and posted information real-time during the workshops.

Figure 4: The xTerramechanics Community: photos of the study participants. (Left) Workshop #1, (Right) Workshop #2.

The new community is already making in-roads toward an integrated and emergent capability to perform life-cycle modeling and simulation of conceptual systems for next-generation missions. JPL scientists are working with Caltech soil mechanicians to characterize simulant properties. JPL engineers have been invited to the conferences of the International Society of Terrain Vehicle Systems. Academic researchers at CMU are working with Caltech for computational interpretation of recent results made possible via particle velocity tracking methods (experimental imaging).

2.3 Education and public outreach

At the beginning of the 1st workshop on xTerramechanics, the study team organized and hosted a half-day introductory course on terramechanics for planetary exploration. The course was advertised within the JPL and Caltech communities and drew a full crowd. The material was presented in an energetic and engaging format, and is now available for public viewing on iTunes or at the KISS xTerramechanics website:
http://www.kiss.caltech.edu/workshops/xterramechanics2011/schedule.html.

In addition to the short course, most of the presentations delivered during the KISS study are also freely available on the KISS website.

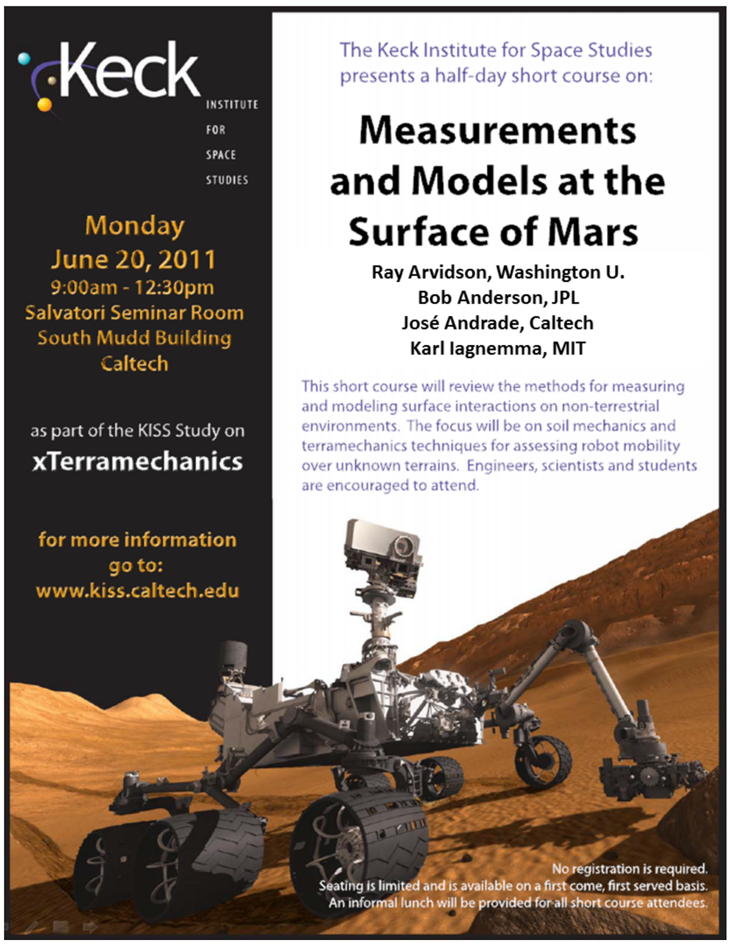


Figure 5: Flyer for Public Short Course held at Caltech.

2.4 Study evaluation

We have found that this KISS study, comprising of two workshops interspaced with a study period, provided an extremely productive environment and a strategically beneficial venue for connecting scientists and engineers from diverse disciplines. The latter in particular made for rich topics of discussion throughout the study, and for a broader examination of regolith-related challenges in NASA missions.

We have also found a relatively tight scheduling of the workshops and of the interim study period to be very helpful. With approximately six weeks between the June 20 opening and August 3, 2011 closing, time was close enough to allow the organizing team to maintain strong workshop continuity. At the same time, the period was long enough to allow the returning participants to generate a fresh set of viewpoints at each workshop. An informal nature of the KISS study facilitated a free exchange of ideas and was of great benefit in breaking down any collaborative barriers.

As unconventional as it may seem, having an interdisciplinary team from experts in the fields of geology, geophysics, and geomechanics, to Mars rover drivers and planetary scientists was a significant contributor to the study success. The variety of scientific and engineering backgrounds enabled all participants to develop a broad and comprehensive picture of challenges and pitfalls in planning for spacecraft-regolith interactions in distant celestial bodies, and to get a clear grasp on the transformative research advances needed to address the challenges.

Inclusion of young postdoctoral researchers and graduate students also provided a fresh perspective and valuable contributions during KISS study exchanges. The informal nature of the workshops appeared to be a great motivator for active participation and an inspiration in the academic and personal growth of these young scientists. In addition, an opportunity to mingle with leaders in their respective fields outside of the work hours, during the lunch and dinner events organized as part of the workshops, no doubt provided lasting connections in their developing careers.

3 Envisioning a New Generation of Science Missions: To the Surface of Planetary Bodies

3.1 Terramechanics: canonical reduced-order model to capture wheel-soil interactions

3.1.1 Introduction to terramechanics

The study of the interaction of wheeled and tracked terrestrial vehicles with natural terrain is dominated by the discipline of terramechanics. The father of this discipline is considered to be M. G. Bekker, author of Theory of Land Locomotion [1,2] and other seminal works, most of which were published between 1950-1960. The post-war period saw intense research focus in vehicle-terrain interaction by the automotive industry and the U.S. Army, and this research found broad application in the passenger vehicle sector, agricultural sector, construction, recreation, and mining industries.

Terramechanics research has historically focused on analysis of large, heavy vehicles (e.g., passenger vehicles, tractors, earthmoving equipment, tanks). This has led to the development of various frameworks and methodologies for predicting vehicle movement over natural terrain, the most notable of which is commonly termed “Bekker theory” or “Bekker-Wong theory” (after J. Y. Wong, another pioneer of terramechanics research [3]). These modeling frameworks are typically semi-empirical or empirical in nature, and draw on extensive resource-intensive experimental testing. They have been shown to be relatively accurate for predicting the performance of large vehicle systems.

KISS Study Question:

How to use reduced-order models (e.g. mobility) to enhance science return?

- *Wheel-soil interactions on granular terrain occur at depth, with slip failure initiated within the regolith. In effect, mobility response reflects regolith properties and can be used as a science detection tool.*
- *Currently, a stream of rover telemetry (e.g. wheel slip, terrain slope) is being collected from the Mars missions (MER, and soon MSL). None of this data is currently used to study the properties of regolith, in the context of geoscience or mission-enabling mechanics.*

However, as a consequence of their empirical nature, while the methods are useful for prediction of large, heavy vehicle mobility, they cannot reliably be used for prediction of small, lightweight vehicle mobility. In the case of empirical methods, this is because the experimental test data driving the methods have been gathered for a distinct class of vehicle systems. In the case of semi-empirical methods (i.e. methods that are grounded in theory, but may contain empirically determined correction factors or constants), this is because the model development relies on assumptions about soil loading and failure mechanics that are not valid for small vehicles.

In the last 15 years, renewed interest in terramechanics has arisen in the context of planetary surface exploration of Mars and the Moon. Despite the fact that planetary exploration rovers are generally of much smaller scale (i.e. smaller size and lower terrain contact pressure) than systems considered under terramechanics theory, there has been significant effort in the research

Reduced-order terramechanics

Strengths:

- *Quick and computationally inexpensive tool for mobility analysis. Successful in describing steady-state wheel or track motion on variety of earth terrains.*

Weaknesses:

- *Parameters largely empirical, and only loosely related to intrinsic 'terra' properties. Inability to extrapolate to new environments.*
- *Off-nominal situations (e.g. high slip-sinkage) and novel terrains (e.g. ripples) not possible without in-situ testing.*

community to apply classical Bekker-Wong theory to rover system modeling. This is largely because there is a lack of competing modeling theory that is specifically targeted at understanding the interaction of small, lightweight vehicles and natural terrain surfaces.

Unsurprisingly, various researchers have concluded that the Bekker-Wong modeling methodology has limitations when applied to small, lightweight rover systems [4,5]. Various modifications of this theory have been recently proposed that have resulted in reasonably accurate performance predictions of small robotic vehicles. While these methods can be considered a "patch," rather than a rigorous re-thinking of the problem, they currently represent the state-of-the-art for rover mobility modeling.

3.1.2 Stresses at the rover-terrain interface

Bekker-Wong theory relies on the analysis of two fundamental relationships: the pressure-sinkage relationship, and the shear stress-shear deformation. In the context of rover mobility, the pressure-sinkage relationship governs the depth that a rover wheel will sink into the terrain—and therefore how much resistance it will face during driving. The shear stress-shear displacement relationship governs the amount of traction that a wheel will generate when driven—and therefore how easily it will progress through terrain and surmount obstacles.

The pressure-sinkage relationship was described by Bekker in the form of a semi-empirical equation that relates normal pressure with sinkage of a plate pushed down into the soil. The proposed relation is commonly referred as the Bekker equation, and provides a link between the kinematics (sinkage) and stress (pressure) of a plate (which can be viewed as a proxy for a wheel or track):

$$p = \left(\frac{\mathrm{k_c}}{\mathrm{b}} + \mathrm{k_\phi}\right) z^n$$

Parameters k_c, k_ϕ, n are empirical constants that are dependent on soil properties, while b corresponds to the plate width. These parameters can be obtained from field tests conducted with a device called a bevameter. The bevameter is a device that records sinkage and normal pressure exerted on a plate of width b while it is pressed into the terrain at constant displacement rate, as illustrated in Figure 6. While collection of such data with a bevameter is possible in terrestrial field conditions, the use of such a device for gathering data on a planetary surface may not be practical or desirable.

The Bekker equation can be used to model the pressure-sinkage relation for a particular running gear geometry (e.g. wheel or track). For planetary exploration rovers, wheels are the primary running gear of interest. For wheels, the Bekker equation can be used to model the stress distribution at the wheel-terrain interface. Specifically, stress can be divided in two components (assuming a two dimensional model, and momentarily ignoring out of plane motion): normal stress and tangential stress. A schematic representation of the stress distribution at a wheel-terrain interface is presented in Figure 7.

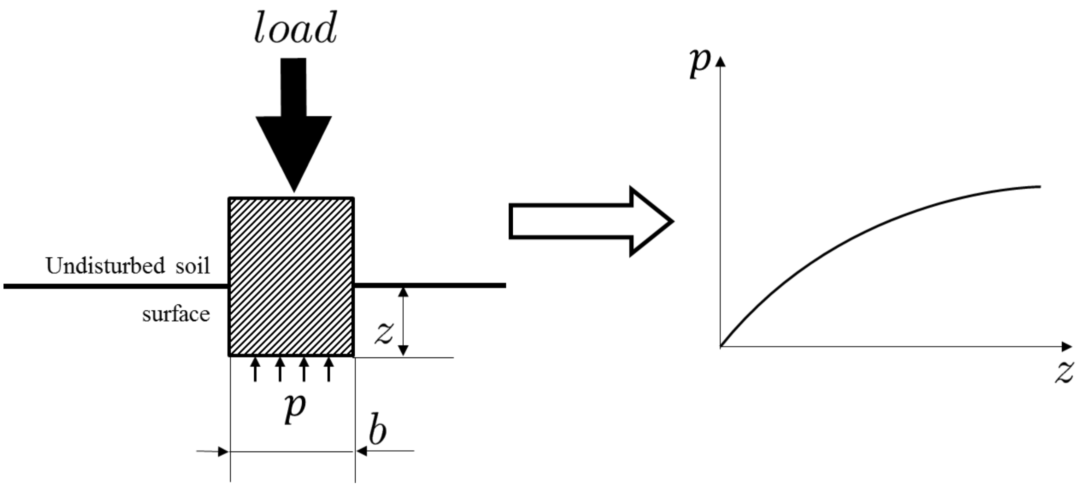


Figure 6: Soil penetration test and schematic of output test data.

Normal stress can be calculated by starting with Bekker's pressure-sinkage relation, and introducing a scaling function intended to satisfy the zero-stress boundary conditions present at the fore and aft points of contact of the wheel with the terrain (known as "soil entry" and "soil exit"). The equation is expressed as a piecewise function, as follows:

$$\sigma = \begin{cases} \sigma_1 = \left(\frac{k_c}{b} + k_\phi\right) z_1^n & \theta_m < \theta < \theta_f \\ \sigma_2 = \left(\frac{k_c}{b} + k_\phi\right) z_2^n & \theta_r < \theta < \theta_m \end{cases}$$

$$z_1 = r\,(\cos\theta - \cos\theta_f)$$

$$z_2 = r\left(\cos\left(\theta_f - \frac{\theta - \theta_r}{\theta_m - \theta_r}(\theta_f - \theta_m)\right) - \cos\theta_f\right)$$

where θ_f is the soil entry angle, θ_r is the exit angle, and θ_m is the angle at which the maximum normal stress occurs (see Figure 7). This equation represents a statement of the normal stress-sinkage relationship for a wheel traveling on deformable soil.

The shear stress-shear displacement relationship is based on the Mohr-Coulomb failure criterion, coupled with a modulation function proposed by Janosi and Hanamoto [6]:

$$\tau_x = (c + \sigma \cdot \tan\phi)\left(1 - e^{-\frac{j_x}{k_x}}\right)$$

where c is the soil cohesion, ϕ is the angle of internal friction, k_x is the shear modulus (a measure of shear stiffness), and j_x is shear deformation:

$$j_x = \int_0^{t_0} v_t dt = \int_\theta^{\theta_f} v_t \frac{d\theta}{\omega}$$

where v_t is the tangential slip. Note that, while some of these parameters are intrinsic soil properties (cohesion and internal friction angle), others are empirical constants (the shear modulus).

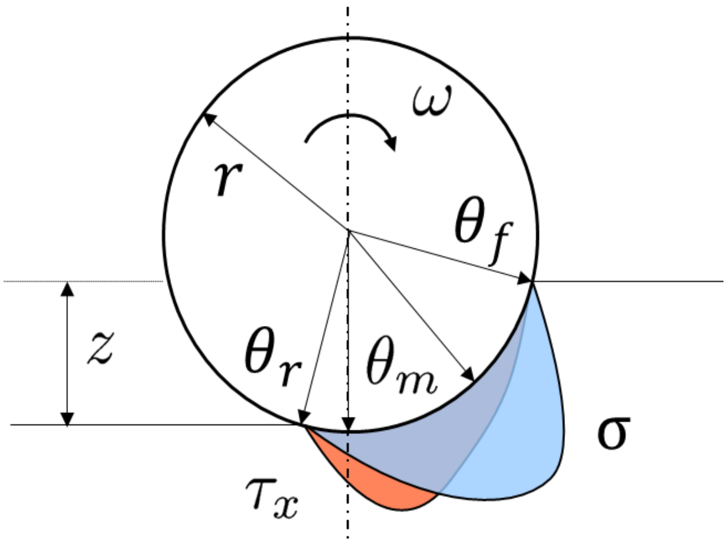


Figure 7: Schematic representation of normal and tangential stress profile along a rigid wheel.

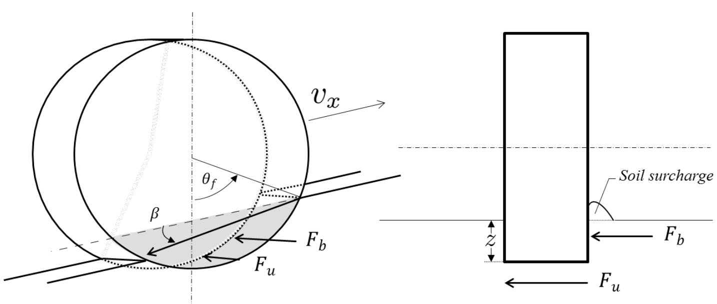


Figure 8: Lateral force generation on a smooth wheel. Lateral force is the product of two components: soil shear under the wheel and soil resistance to plowing at the wheel sidewall.

A key aspect of vehicle mobility that is not considered in classical Bekker-Wong theory is lateral forces. Lateral forces are significant because they give rise to turning motion, and sliding on slopes. Lateral forces on a wheel originate from two factors: shear forces acting between the wheel and soil at the bottom wheel interface, and “bulldozing” (i.e. plowing) forces acting on the wheel sidewall (see Figure 8). Various researchers have proposed models for these lateral force components. Lateral shear forces are typically modeled in a manner similar to longitudinal shear forces:

$$\tau_y = (c + \sigma \cdot \tan\phi)\left(1 - e^{-\frac{j_y}{k_y}}\right)$$

$$j_y = \int_0^{t_0} v_y dt$$

where v_y is the lateral velocity of the wheel, $v_y = v_x \tan\beta$, and β is the wheel slip angle with respect to the travel direction of the robot body. Bulldozing forces are modeled in a manner similar to that of a flat blade moving through soil. The solutions of the cutting blade problem are based on Terzaghi’s solution for soil bearing capacity [7]:

$$\sigma_B = \gamma z N_\gamma + c N_c + q N_q$$

$$N_\gamma = \frac{2\left(N_q + 1\right)\tan\phi}{1 + 0.4\sin 4\phi} \quad N_c = \frac{N_q - 1}{\tan\phi} \quad N_q = \frac{e^{(1.5\pi - \phi)\tan\phi}}{2\cos^2(\pi/4 + \phi/2)}$$

with the various constants present in this equation once again a mixture of intrinsic soil properties and empirical constants.

3.1.3 From soil response to rover mobility

Once the stress profile acting on a wheel has been completely defined, these profiles can be integrated to determine the net forces and torques on the wheel, which are then summed over all wheels to compute overall vehicle motion.

Traction forces generated by a wheel can be decomposed in two components: a thrust component, which acts to move the vehicle forward; and a compaction resistance component, which resists forward motion. Thrust, *T*, is computed as the sum of all shear force components in the direction of forward motion:

$$T = br\int_{\theta_r}^{\theta_f} \tau \cos\theta \, d\theta$$

Compaction resistance, R_c, is the result of all normal force components acting to resist forward motion, and can be thought of as the net resistance force provided by the soil:

$$R_c = br\int_{\theta_r}^{\theta_f} \sigma \sin\theta \, d\theta$$

The net longitudinal force, also termed the drawbar pull, *DP*, is calculated as the difference between the thrust force and resistance force. *DP* is the resultant force that can either accelerate the wheel, or provide a pulling force at the vehicle axle.

$$DP = T - R_c + F_g$$

The importance of drawbar force is obvious, since a positive drawbar force implies that a rover can generate forward motion on a particular patch of terrain, while a negative drawbar force suggests that forward acceleration is impossible. For a six-wheeled rover such as MER or MSL, the individual drawbar forces acting at each wheel would be summed, and the net force would serve to either accelerate or decelerate the rover.

Torque, *M*, is the resultant of shearing action along wheel rim, and can be calculated as:

$$M = br^2\int_{\theta_r}^{\theta_f} \tau d\theta$$

The lateral force is the resultant of both lateral shear forces (F_u) and lateral soil resistance (F_b) at the sidewall:

$$F_u = br \int_{\theta_r}^{\theta_f} (c + \sigma(\theta) \, tan \, \theta) \left(1 - e^{-\frac{j_y}{k_y}}\right) d\theta$$

$$F_b = \int_{-r \sin \theta_f}^{r \sin \theta_f} [\gamma N_\gamma f(x) + c N_c + q N_q] f(x) dx$$

where $f(x) = \left(\sqrt{r^2 - x^2} - z_0\right)$. The total lateral force, L, can thus be computed as:

$$L = F_u + F_b \sin \beta$$

The sinkage of a wheel can be calculated by solving a vertical force equilibrium problem, which enforces the fact that the force resisting wheel penetration into the soil must be balanced by the vertical load acting on that wheel.

$$W = br \int_{\theta_r}^{\theta_f} (\sigma \cos \theta + \tau \sin \theta) d\theta$$

3.1.4 Limitations of terramechanics for planetary rover modeling

The above equations embody the key elements of Bekker-Wong terramechanics theory. Implicit in this theory is the assumption that the penetration of a wheel into soil can accurately be approximated by the penetration of a flat plate. This assumption is tenuous for rovers, since the curved geometry of small rover wheels is highly dissimilar to that of a flat plate. Also, Bekker theory assumes that wheel traction is governed by soil failure (rather than slip at the wheel-terrain interface). For lightweight rovers with low terrain contact pressure, this may not always be true.

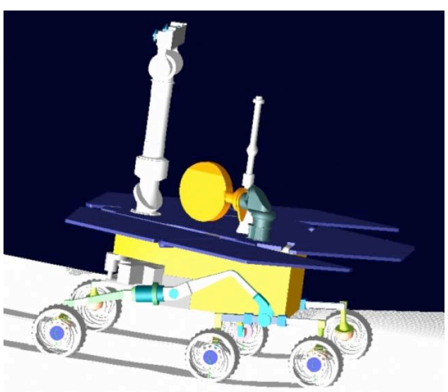


Figure 9: Example of ARTEMIS software for modeling the influence of regolith terrain on the rover body dynamics.

Despite these significant limitations and drawbacks to Bekker-Wong theory, it arguably represents the current state-of-the-art in rover mobility modeling, as shown in Figure 9. In addition to the drawbacks to Bekker-Wong terramechanics theory that have previous been mentioned, a key limitation for planetary rover modeling is the lack of capability to analyze the effect of a variable gravitational field on soil strength. Another key limitation lies in the lack of a capability to model cases of severe wheel sinkage and slippage, which was experienced by both MER rovers on numerous instances (and, in the case of the Spirit rover, led to immobilization, and the end of Spirit's campaign as a mobile science instrument).

3.2 Continuum models and plasticity theory

3.2.1 Overview: modeling of geomaterials

Continuum models, or more precisely continuum constitutive models, are (with a few exceptions) phenomenological in nature. They are based on empirical evidence, inferred through extensive laboratory testing or some general field observations. Theory of plasticity provides a general framework that can be used to treat a great variety of materials that are not solely elastic. Geomaterials invariably fall into this category, with a canonical example of sand in which re-arrangement of grains due to imposed loads is often non-recoverable and contributes overwhelmingly to the plastic behavior of the material.

Experimental tests on a variety of geomaterials, from clays to sand to rock, indicate a great deal of grain-scale complexity. The grain-scale processes, in turn, conspire to create an overall macroscopic response, i.e. phenomena determined at the laboratory or the field scale. To encapsulate many of the key macroscopic phenomena, plasticity models are custom tailored with specific mathematical features designed to mimic the observed. Examples are given in the following Section 3.2.2.

The underlying problem of phenomenology is the following: in designing plasticity laws for specialized applications, as exemplified by those encountered in extra-terrestrial environments, little apriori testing of such materials exists. And even if materials could be returned and were available for closer examination, at present, there would be little material and precious little means to reproduce the source environments (e.g. sub-gravity, vacuum, etc.). Constitutive plasticity laws that take into account the underlying physics of grain-scale processes are sorely needed, if such environments are to be modeled faithfully. Specific ways of overcoming the problems of phenomenology are given in Section 3.4.

KISS Study Question:

Can existing plasticity framework be extended to xTerra applications, e.g. for modeling of (hydro) mechanical behavior of regolith?

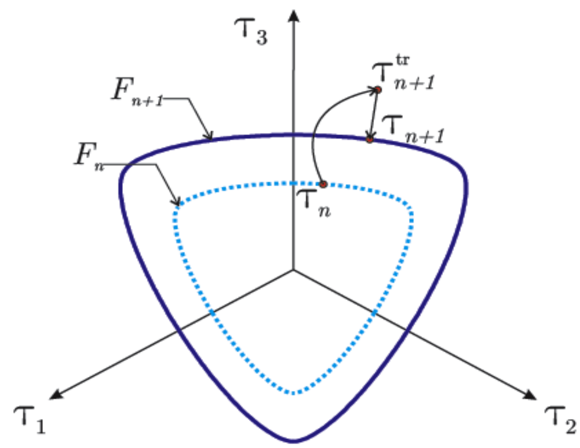
- *Terrestrial testing and modeling campaign of lunar soil returned during Apollo missions indicate remarkable flexibility of plasticity models to describe key mechanical features of regolith. Grain-based analysis provided physical basis for inferred plastic internal variables.*
- *Extrapolation to other novel regolith types, and to novel environments is, however, severely limited. For this to change, grain-based processes will somehow need to be integrated into plasticity framework via e.g. multi-scale techniques.*

3.2.2 Constitutive models of geomaterials

Non-linearity and plasticity in geomaterials can arise from a variety of physical processes. For example, granular materials or fractured rocks usually become stiffer and their elastic modulus increases under high confining pressures. This effect is a physical result of increased contact area between individual grains in granular materials, or closing or bridging of open cracks in fractured rocks. Non-linear theory of elasticity is able to describe the observed, but only in a macroscopic sense, with little information of the micromechanical processes at play.

Non-recoverable (plastic) processes tend to be more complicated. Plasticity of geomaterials tends to be exacerbated under low confinement because many geomaterials are frictional in nature. By extension, this suggests that gravity will invariable play a role in their behavior as well [8]. Cohesion may also become dominant for smaller particles in near-vacuum environments [9].

A classic Cam-Clay model and a capped Drucker-Prager model provide perhaps the most popular plasticity frameworks in geomaterials. The essential parameters that feed the models are: the void ratio (related to material porosity), the current stress state (often split into volumetric and shear components), stress history, and other variables related to material 'structure' (this can mean anything from grain crushing to anisotropy). The models are characterized by their ability to describe material compressibility (plastic changes in void ratio); smooth transitions from the elastic to the plastic regions, and vice versa, via yield and plastic potential surfaces; changes in the point of elastic-plastic transition via movement of the yield surface (hardening or softening) based on changes in the void ratio or accumulated plastic strains; and others. From the preceding features, little can be learned directly in the way of physical processes at play or the causality between the processes and the parameters. Nevertheless, history has revealed that these models are well behaved in terrestrial and even extra-terrestrial environments, as exemplified by tests on returned lunar soil (next Section 3.2.3). Key features of the plasticity framework are shown in Figure 10.



Hooke's law $\dot{\boldsymbol{\sigma}} = \boldsymbol{c}^{\mathrm{ep}} : \dot{\boldsymbol{\epsilon}}$

Additive decomposition of strain $\dot{\boldsymbol{\epsilon}} = \dot{\boldsymbol{\epsilon}}^{\mathrm{e}} + \dot{\boldsymbol{\epsilon}}^{\mathrm{p}}$

Convex elastic region $F(\boldsymbol{\sigma}, \boldsymbol{\alpha}) = 0$

Non-associative flow $\dot{\boldsymbol{\epsilon}}^{\mathrm{p}} = \dot{\lambda} \boldsymbol{g}, \qquad \boldsymbol{g} := \partial G / \partial \boldsymbol{\sigma}$

Figure 10: (Top) Example of a hardening yield surface shown in the plane normal to the hydrostatic axis. The model is representative of terrestrial geomaterials. (Bottom) A recipe of an elasto-plastic framework. The yield function F and the plastic potential G are circled in blue and red respectively. Parameters that describe F and G (including softening/hardening) are phenomenological in nature. Little can be learned in the way of underlying physical processes from continuum alone.

3.2.3 Lunar regolith

Repeat trips to and return missions from our moon have provided a unique opportunity by which to study regolith. Geologic process by which the lunar regolith is produced is very different from those encountered in terrestrial environment. Lack of atmosphere on the moon has translated to a constant barrage of meteors, as evidenced by its cratered surface. This has caused continuous near-surface grain fragmentation, with granular material covering essentially our entire moon.

Rudimentary in-situ tests on lunar surface via e.g. cone penetrometers indicate a near surface friction angle and cohesion on the order of 50 and 1 kPa respectively [10], the latter value comparable in order of magnitude to cohesion of unsaturated sand. Return of more than 100 kg of lunar regolith during Apollo missions in the 1970s [10] has also enabled terrestrial testing of lunar regolith under controlled settings. Some conclusions based on the observed geologic features and mechanical parameters are shown in Figure 11. Because of their geologic history, lunar grains are much less rounded (sharper) than terrestrial grains and contain glassy granules formed as a result of high energy of meteor impacts. These features have a direct influence on and are in fact exemplified by the mechanical properties of lunar regolith.

High degree of angularity and grain sharpness of lunar regolith affects the bulk mechanical properties in two ways: (1) it results in relatively high shear strength due to non-spherical grain shape (2) leads to high apparent cohesion via grain interlocking. The presence of glassy agglutinates also makes the material easily crushable [11]. Tests also showed strong dependence of elastic moduli on confinement level and packing density [12].

In summary, lunar regolith possesses geologic characteristics unlike those found in terrestrial environment. They are a direct result of its geologic past and are ingrained in the mechanical properties of its regolith. Existing plasticity framework is capable of describing the behavior of the lunar regolith, based on tests conducted of returned regolith under controlled settings here on Earth. Grain-based or micromechanical analysis has provided a physical support for the measured parameters in the plasticity models. However, our current inability to incorporate grain-based processes directly into the plasticity framework means that our ability to extrapolate regolith mechanics to environments other than our moon is severely limited.

3.2.4 Beyond our moon

Clues about geologic histories of rocky planets, moons, and other celestial objects is ever growing, a direct result of the continued exploration of our solar system. The nature of regolith is also an ever-growing area of planetary

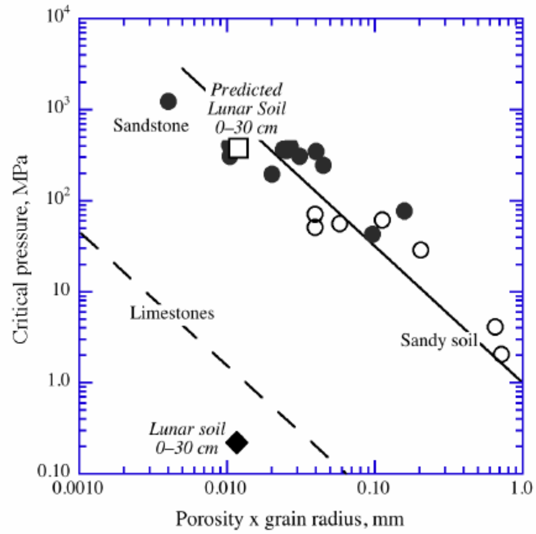


Figure 11: An example of unusual physical features of lunar regolith, as compared to earth soil. (Top) Low values of the Critical Pressure likely indicate the low crushing strength of glassy agglutinates found in lunar soil, a byproduct of repeated surface impacts. (adopted from [11]). (Bottom) High shear strength and/or cohesion of lunar soil, due to presence of interlocking particles, as evidenced by the steep landing 'foot' print angles (from Apollo 12 photograph, adopted from [14]). The print, left over by a previous lunar mission, appeared intact more than 2 years later.

research, and geology in particular. Based on a present knowledge of extraterrestrial regolith, a key environmental distinction between the Earth's deposits and those of other solar celestial bodies is the presence of life, and its influence on soil-forming processes [13]. At once, this also suggests that the best regolith analogues are to be found in almost-abiotic environments here on Earth. In charting the course for the continued exploration of the mechanical properties of regolith, and development of its simulants, such analogues should be the subject of detailed studies.

3.3 Computational methods

3.3.1 Finite element method

The finite element method (FEM) is a powerful numerical technique for finding *approximate* solutions of partial differential equations (PDE). The solution approach typically relies on transforming the PDE into a system of ordinary differential equations. These can then be numerically integrated using standard techniques, in space and time, e.g. backward Euler's method.

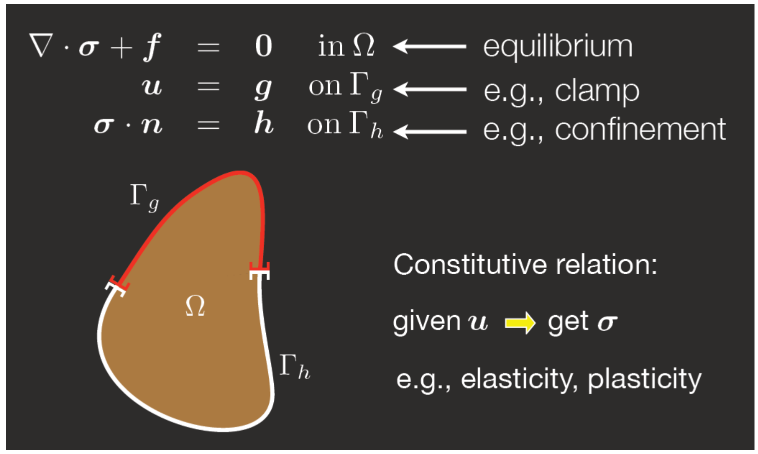


Figure 12: Boundary decomposition in FEM.

There are several steps involved in development of an FEM solution, as shown in Figure 14. These include setting of the bounding domain geometry, discretization of the computational domain, prescription of elemental material properties, and finally (approximately) solving the resulting (linear or non-linear) system of equations.

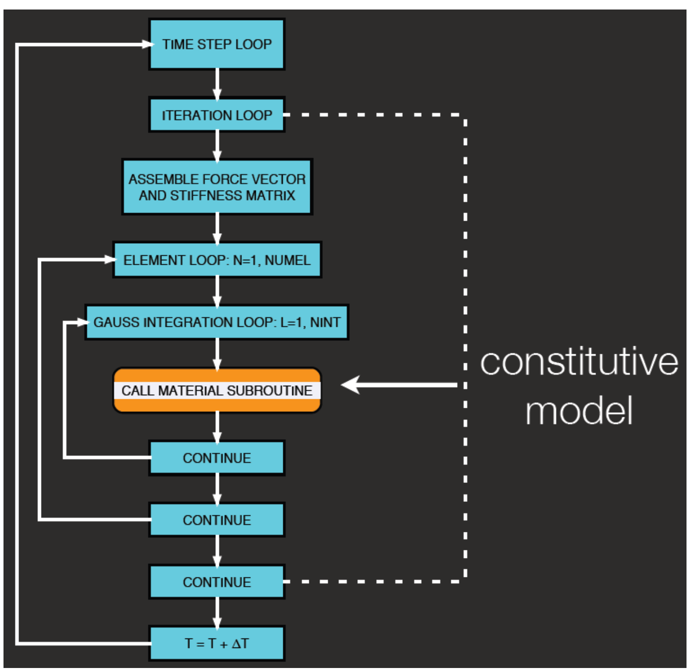


Figure 13: Typical FEM implementation. The workflow indicates that constitutive models, i.e. the material subroutine, are at the heart of any successful finite element model.

In the context of modeling mechanical systems, the FEM recipe is outlined in Figure 12. Constitutive relations provide a link between the stresses and nodal deformations. The method typically treats the deformations as unknowns. Element-level stresses and strains can subsequently be inferred. Boundary conditions play an important role in the overall solution. Deformations and forces (stresses) must be enforced at all element nodes, but not both at the same location. Numerical integration in space is performed with the help of gauss integration points.

As shown in Figure 13, a material constitutive relation (material subroutine) resides at the heart of FEM. In attempts to model novel material systems, this relation also happens to be the Achilles heel of FEM. In other words, the FEM solutions can only be as good as the underlying models used to describe the material being modeled, even if the equilibrium solutions can be determined exactly.

Cutting-edge FEM techniques with direct relevance to terramechanics include Arbitrary Lagrangian Eulerian (ALE) formulation [15], adaptive (re)meshing of the computational domain, and the Coupled Eulerian-Lagrangian (CEL) methods [16]. Liqun Chi of industry-leading Caterpillar presented some of the practical applications of these methods. The aforementioned advances in computational modeling have enabled simulations of large deformation problems that are capable of handling material flow, tear-out, and re-joining [17]. No images from Caterpillar are available for this report due to the proprietary nature of their work.

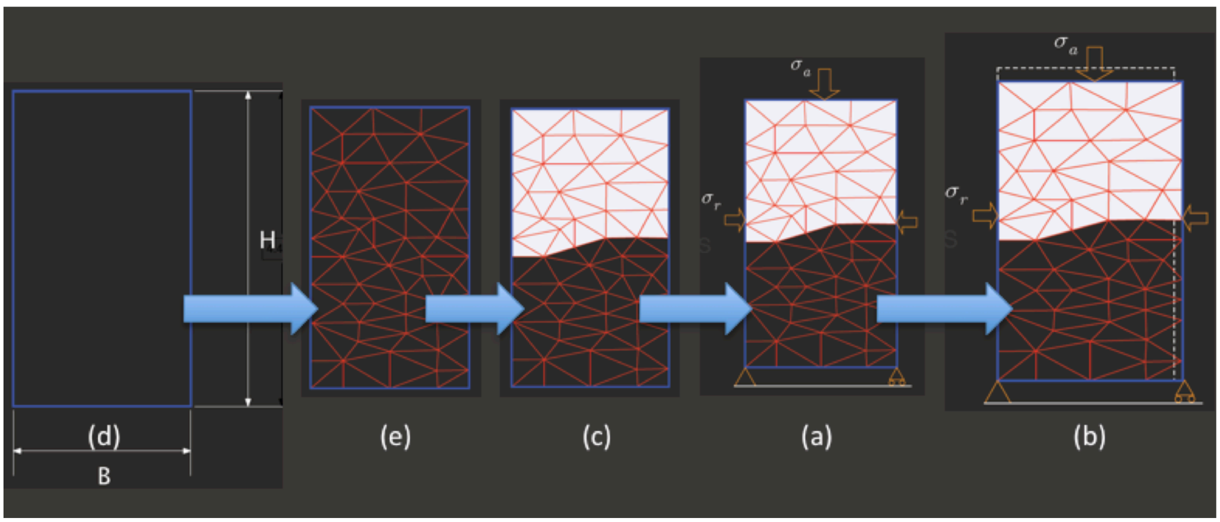


Figure 14: Steps in the FEM. a) Set geometry. b) Discretize domain. c) Set material properties. d) Set boundary conditions. e) Solve the matrix system of equations.

3.3.2 Discrete element method

In nature, granular materials constitute fundamental ingredients of many geomaterials, including soils and rocks. The behavior of granular systems is encoded at the particle scale, propagating all the way to the macroscopic scale. Its discrete nature, therefore, is of crucial importance for the understanding, modeling, and prediction of the behavior of such systems.

In an effort to develop the discrete mechanics for granular matter, Cundall and Strack [18] originally proposed the discrete element method (DEM). In DEM, rigid particles are governed by the Newtonian dynamics and are allowed to interact with each other by contact. A DEM simulation is started by assigning the initial position, orientation, and velocity for all particles in a system. Time stepping is most often explicit, such that forces at one time step control the acceleration (and thus the motion) in the next step. The process is repeated until the end of a simulation. At each time step, the forces acting on the particles are computed from the relevant physical laws and contact models (Figure 15). These may include friction, gravity, and other potentials, such as cohesion, electrostatic attraction, and others.

DEM has become an important tool in investigating micro-scale mechanisms in granular materials [19,20]. Among other variables, under investigation have been the effects of shape and porosity (especially on the important dilatancy properties of granular materials), using polyhedral blocks and ellipsoids. The applications include generation of constitutive relations for granular materials [21,22], investigation of shear banding importance in strength [23], and simulation of fluidized beds [24]. DEM is also a widely accepted as an effective method for addressing granular flows, powder mechanics, and even rock mechanics.

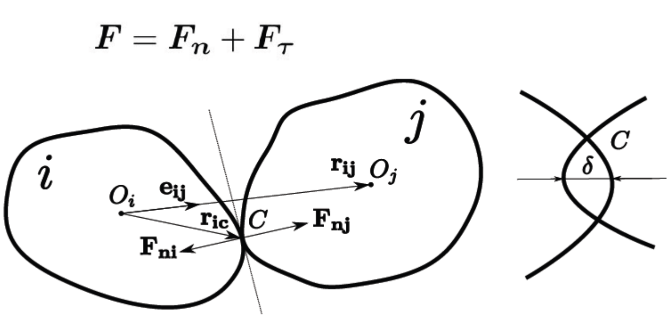


Figure 15: Detailed contact model used in DEM.

The beauty of DEM is its simplicity [25], and perhaps the reason for its enormous popularity. Unfortunately, DEM is relatively computationally intensive, which limits either the length of the simulation or the number of particles that can be modeled. Part of reason for this is that in many granular materials, the scale of a particle is far removed from the relevant problem scale. A great example is furnished by plain beach sand – assuming an average particle diameter on the order of 20 micrometers, more than 100,000 particles may fit inside a box with side length of 1cm. In addition, sand (quartz) particles are relatively stiff, which from the point of view of computational stability forces the incremental time steps to be extremely small, on the order micro or even nano seconds. And beach sand is a relatively coarse granular material. What of the materials that have particle size equal to that of household flour or silt? The aforementioned computational (but not physical) limitations of DEM suggest that faithful full-scale computations of engineering problems using DEM are still at a distance.

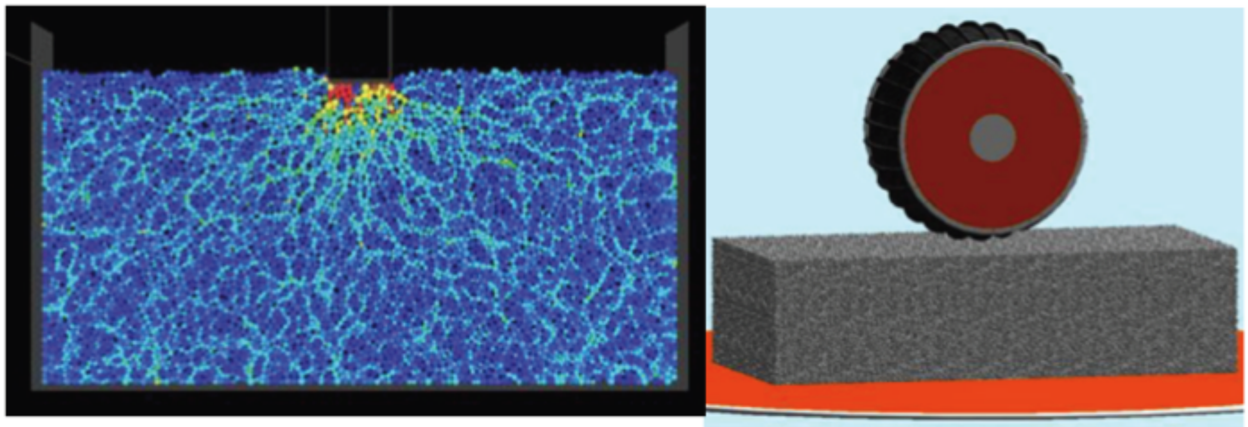


Figure 16: (Left) Rigid punch penetrating a box of particles, simulated using DEM. Highly stresses load paths, termed load chains, emanate from the area of surface contact [26]. (Right) Case study: Mars exploration rover wheel digging simulation using DEM. Particles and material properties were scaled up in order to minimize computational cost [27].

3.3.3 Contrast: DEM and FEM in discrete material systems

Fundamental DEM, FEM contrast

- Continuum methods, including FEM, are perhaps the most powerful and versatile tools for modeling of engineering systems, including discrete systems. Continuum descriptions tend to average out multiple physical processes into simpler numerical expressions. This makes the methods phenomenological when applied to discrete systems.
- Discrete methods, including DEM, model the explicit dynamics of particle assemblies, and in the process are able to faithfully reproduce phenomena unique to discrete systems. Discrete descriptions are able to account for micro-mechanical interaction between individual grains. This makes the methods physics-based when applied to discrete systems.

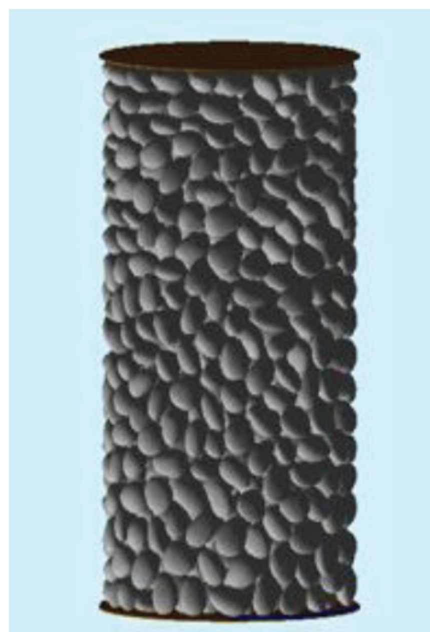


Figure 17: A DEM study: simulated triaxial test accounting for the particle morphology (J. Johnson, KISS study presentation, 6/22/2011).

Future of discrete material modeling: Workshop conclusions

Workshop discussions indicated a clear need for physics-based approaches, even if computational expense may be too great for direct treatment of full-scale engineering problems (for methods to overcome this problems, reader is referred to multi-scale approaches, Section 3.4). DEM research results indicate that particle shape and contact friction and cohesion, among other variables, are too important too ignore, particularly in space related applications. It is likely that DEM will set the stage for an apriori determination of soil properties based on the expected morphological and geological characteristics. Heavy emphasis should be placed on the ability to describe complex particles shape via DEM.

As a result, quantitative validation of DEM models should be continued, with particular emphasis on testing the grain-based physical properties of discrete systems. For example, in addition to employing fully imaged tri-axial and shear-box equipment for the purposes of testing and validation of material models (Section 3.5), micro-scale grain contact properties should also be tested under carefully controlled environments. The latter provide physical grain-interaction laws, a necessary input into discrete system simulations.

3.4 Multi-scale physics: Synergy of computational methods

3.4.1 Why multi-scale in space applications?

Thus far, the backbone of models that attempt to be relevant and predictive in dealing with geo-materials at the field scale, from soft soils to hard rocks and concrete [28,29], has been furnished by numerical techniques such as the finite element method (FEM). The FEM models have relied on continuum mechanics techniques that ultimately invoke phenomenological constitutive models [30]. These phenomenological models have occupied an important place in mechanics of these materials, in large part due to their versatility and ability to capture many salient features exhibited in the materials' natural environment, as discussed in Section 3.2. However, the models have had the luxury of modern laboratories as well as direct access to materials that they are trying to describe. This in turn allows the models to be calibrated for the material at hand and typically the type of loading that is expected. In this way, the continuum models have managed to remain descriptive (rather than physics based) as well as predictive.

Phenomenological models face severe limitations when dealing with applications outside of the conditions for which they were calibrated or designed. There are numerous examples of such shortcomings in terrestrial applications. Understanding the constitutive behavior of shear bands, for example, has been at the forefront of geomechanics for decades. These failure or localization bands are extremely important features and their constitutive response can differ significantly from the bulk material during failure. Modeling the bands phenomenologically, via continuum models, has historically posed significant challenges [31,32]. Shortcomings of continuum models are especially acute in space-related applications where environmental conditions lie far outside of the terrestrial design envelopes and data is sparse (with perhaps a unique exception of lunar regolith [33], as discussed in Section 3.2.3).

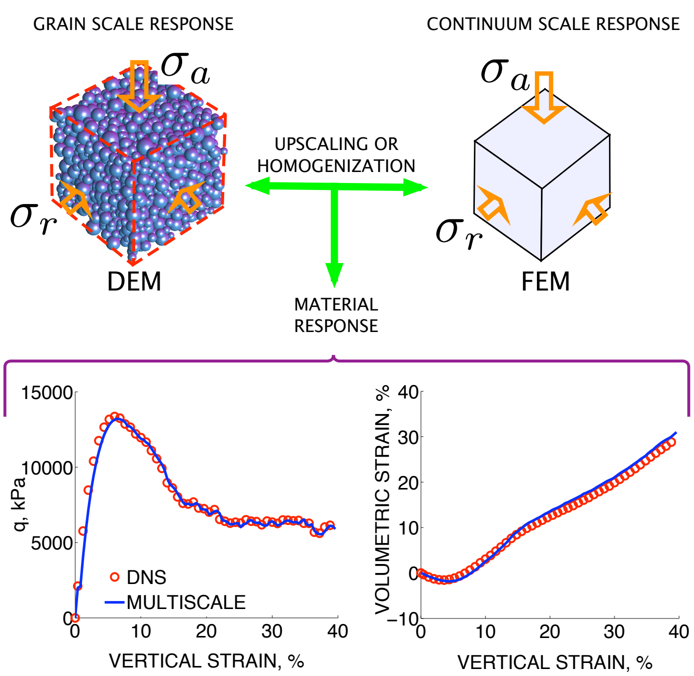


Figure 18: Multi-scale concept and comparison with full-scale DEM calculations under triaxial compression tests. A material is split into individual elements (boxes), which upscale a limited number of parameters [34,35].

How can a phenomenological model account for the differences in a gravitational field between our planet and another celestial body, especially smaller bodies such as a moon or an asteroid? How can a phenomenological model account for the extreme differences in the shapes of grains, the fundamental building blocks of regolith that covers many celestial bodies? With a phenomenological model, how can we hope to add mechanics as a scientific tool that can unravel the very physical phenomena encountered on the surfaces of complex celestial systems; employ the mechanics of geologic materials to explain the differences between the geologic histories of our planet and another celestial body; unearth or provide sound evidence of tectonic mechanisms by which surface regolith evolved? The answer clearly involves incorporating the underlying physical processes into the macroscopic geomaterial models.

To accomplishing above-stated task requires passing important bits of information from the lower scale (the scale of relevant physical processes) to the continuum scale (the scale used to describe the 'average' material behavior via e.g. FEM). Multi-scale methods attempt to do just that, i.e. bridge the two (or more) scales of importance. Precisely how this can be done and what physical processes are of importance to geomaterials is the subject of the following discussion. One such multi-scale model for granular materials is shown in Figure 18.

3.4.2 Underlying physical processes and micromechanics in granular media

Micro-mechanical models are ideally suited to handle the evolution of the granular structures without having to resort to phenomenological laws intrinsic in the continuum models of geo-materials. The discrete nature of granular materials has indeed motivated the development of the discrete element method (DEM) [18]. Since its conception, DEM has been used to investigate the micromechanical features of granular behavior [36,37]. The complexity of contact detection algorithms inherent to the method (especially for more general-shape particles) coupled with the enormous number of particles needed to truly describe real grain-based materials have kept DEM away from most field-scale engineering problems. And as a result, DEM has not yet been able to serve as a truly predictive tool it was designed to be.

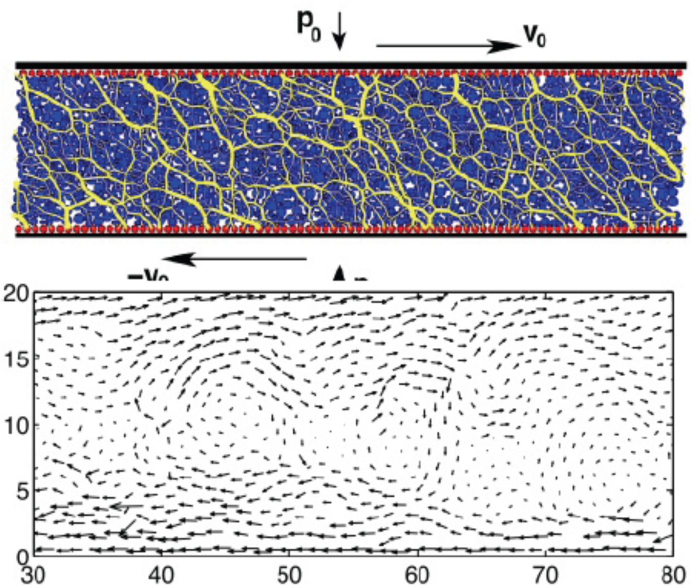


Figure 19: An example of grain scale load-chains (top) and fluid-like vortices (bottom), microscale features encountered under shear-type loading of granular media (images from [38]).

Examples of the physical complexities in granular media are shown in Figure 19. Granular materials resist load via individual contacts between the adjacent grains, forming structured load chains in response to external stimuli (Figure 19, top). During failure, e.g. during shear banding, the load chains can re-align and buckle. This can lead to vortex-type structures in the sheared layers of the material, reminiscent of the shearing response of fluids (Figure 19, bottom). None of these features are explained by the phenomenology of continuum models.

To enable the physics-based modeling of field-scale problems, current state-of-the-art in computational modeling has evolved to take advantage of both DEM, an elegant method of capturing the underlying physical processes on a small scale, and FEM, an efficient and time-tested method of tackling problems at their real scale.

It is important to note that FEM need not only mean solid-state behavior of granular materials, although the discussion here has been limited to this scenario. Granular materials, and thus regolith, can take on a solid-, fluid-, or a gas-like state, even while the individual particles that make up the material remain solid. In such a case, an appropriate FEM material model (fluid or solid) would need to be used. The relationship between the material state and external load state would depend on the environmental conditions, e.g. gravity and atmospheric pressure among others. This precise nature of this relationship can only come from physics-based material description.

3.4.3 A multi-scale recipe for geomaterials

Here we provide an example of a multiscale model in geomaterials. The model does not represent the only way to pass the important bits from information from the micro to the macro scale, but it does appear to be the simplest and at once robust in dealing with granular materials.

Consider a simple Drucker-Prager type elastoplastic model with linear elasticity. As shown in Figure 20a, the yield surface F and plastic potential G are both functions of the stresses and the mobilized frictional resistance μ and dilatancy β, so that F = F(p, q, μ) and G = G(p, q, β). Geometrically, μ and β are the local slope of the yield and plastic potential functions, respectively, in an invariant space defined by the hydrostatic pressure p and the deviatoric (shear) stress q. The name of the game in plasticity models is to update the evolution of μ and β, as prescribed by a hardening or softening law, a phenomenological relation. Within the present multiscale model, the evolution of the internal plastic variables, μ and β, are inferred directly from the microstructure, e.g. via underlying DEM calculations. In this way, the key concept behind the multi-scale framework is simple and reduces to the following, as shown in Figure 20b: use the current boundary conditions to 'probe' e.g. a sample DEM micro-structure to obtain μ and β which are upscaled back to the plasticity model within the FEM code.

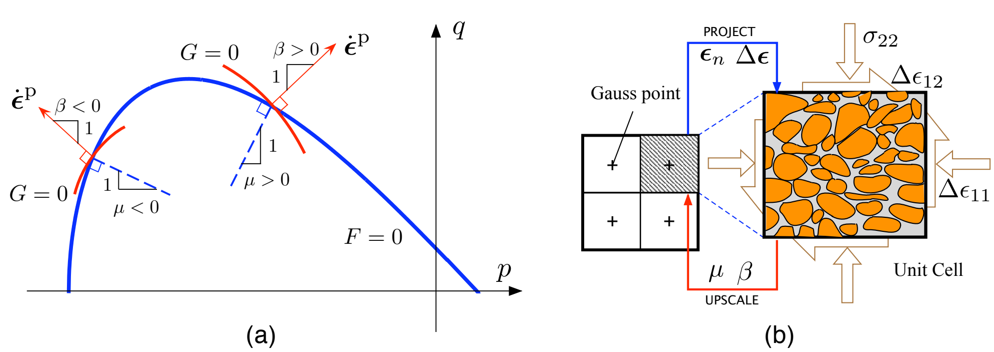


Figure 20: A muti-scale concept: (a) generalized Drucker-Prager model in shear-pressure space and showing the geometrical role of μ and beta and (b) multi-scale probing concept where the state (stress and strain) is passed from the FEM to the DEM where the plastic internal variables μ, are calculated and upscaled back to the FEM.

The probe can be seen as an analog to a simple shear test 'on-the-fly' where the principal stress is imposed as confinement and the rest of the boundaries in the unit cell undergo an incremental strain, allowing the material to naturally mobilize friction and dilatancy. The average microscopic stresses and strains can then be obtained by invoking well-established techniques in the DEM community [39,40]. The dilatancy and mobilized friction are then updated from the micro-mechanical stresses and strains so that $= v/s$ and $\mu = -q/p$. As usual, the dilatancy is the ratio between a change in volumetric strain and a change in deviatoric strain and the friction is the ratio between the shear and pressure stresses.

There are multiple exciting advantages to this approach and some challenges to be resolved. The challenges include the potential loss of symmetry in the micro-mechanical stress (e.g., inside shear bands), which would require the extension of the method to Cosserat (polar) continuum theory [41,42]. Also, the application to contractive sands and cohesive materials remain to be explored.

Nevertheless, the advantages outweigh the challenges and open the door to updating material behavior wherever necessary and with accurate stress-paths. Also, the method is, by definition, parallelizable as each cell is independent of the other and can be accessed individually from the FEM. This technique, linked with DEM and guided by real microscale experiments, e.g. X-ray CT, have the potential for an ambitious characterization campaign of granular media.

3.4.4 Future of multiscale

Endowing the continuum models with the underlying physical processes makes the models not only truly predictive, but also opens doors to fundamental description of behavior of granular materials, regardless of the external environment. This furnishes the ultimate advantage of the successful multiscale schemes. In turn, the multiscale paradigm promises to be transformative in a wide range of mission-critical spacecraft-regolith interactions outlined in this report. Just as importantly, a significant improvement in understanding of the granular materials and their interactions with external stimuli would also enable mechanical models of geologic materials to be used a new generation of scientific instruments.

3.5 Testing and model validation across scales

3.5.1 Introduction

The analytical and numerical models described in this document all require rigorous validation before integration into any part of the mission life cycle. The nature and scale of a particular model dictates its validation strategy. For example, models that predict the motion of individual regolith particles, or groups of particles (e.g. DEM methods), should logically be validated through experiments that can explicitly measure soil particle motion. Here, various model validation/registration methods are described, at scales ranging from the micro-scale, to the meso-scale, to the macro-scale.

3.5.2 Micro-scale model validation/registration

Model validation/registration at the micro-scale implies the ability to correlate the predicted and actual motion of individual particles of regolith when subjected to an external load—for example, from a rover wheel, drill bit, or spacecraft landing pad. This type of validation is valuable because it can yield fundamental insight into the specific deformation and failure mechanisms of granular materials. However, such validation is challenging primarily due to the scale of the particles of interest, and the (typically) three-dimensional and time varying nature of particle motion.

Experimental methods for measuring individual grain particle motion based on x-ray scanning during mechanical testing have recently been developed [43,44]. The wide grain-size distribution that is typically present in regolith, as well as the highly variable grain shapes, create new challenges in obtaining high-quality grain kinematics from sensor data. The essence of the problem is that the 3D images from tomography are maps of x-ray attenuation coefficients (which are strongly related to density), however it is difficult to precisely identify individual grains in these

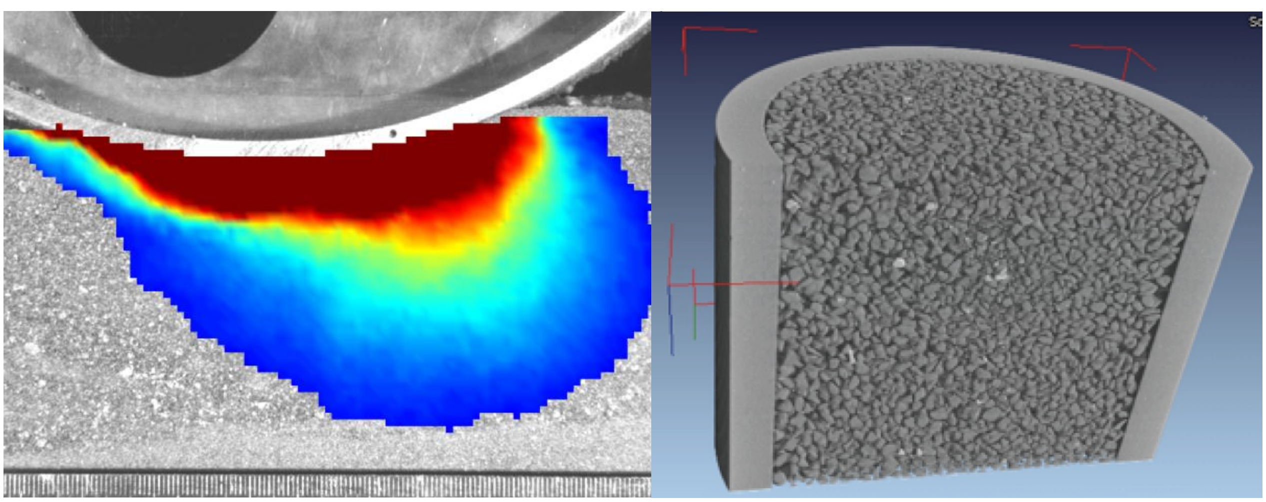


Figure 21: (Left) Preliminary results from PIV test apparatus optimized for soil imaging, displaying measured velocity field in Mars simulant subjected to loading by MER-scale rigid wheel undergoing moderate slippage. (Right) 3d reconstructed tomographic image of a granular material, during an in-situ test using a tri-axial shearing apparatus.

images. Accurate characterization of individual grains, and grain-to-grain contacts, is essential, since they transmit the applied loading through the granular system, and are known to be crucial to mechanisms of plastic strain.

These technical challenges are currently being addressed through the development of a "Discrete" Digital Image Correlation (DIC) approach [44] and a Particle Tracking approach [43]. Once the presence and the orientations of contacts can be accurately established, the evolution of the contacts with respect to the loading must be measured. Unlike tracking of grains, contacts are ephemeral, and so can be created and destroyed during deformation. If a contact persists over an increment, it may remain stationary, it may slide, or rotate, and all this can only be measured by comparing the grains that are in contact. Further research is required to establish a framework for characterizing these different possibilities of contact evolution.

Another approach to micro-scale testing being pursued relies on analysis of images captured by a high performance imager of a volume of soil subject to loading. In this methodology, a volume of regolith simulant is confined in a container with one or more transparent walls. Controlled loading is applied on one more of the container walls, and (planar) images of soil motion captured by the imaging system. Particle Image Velocimetry (PIV) methods are then applied in software to track unique features across consecutive image frames, allowing detailed measurements of the soil kinematics (see Figure 21).

Testing & Validation Advances:

- *In recent years, well-established methods for terrain and terrain-machine testing have been complemented by a host of grain-scale imaging tools.*
- *High energy X-rays, and high-speed and resolution imaging have been at the forefront of the experimental renaissance. This has allowed for a non-destructive examination of fundamental grain-scale processes, from shear banding at failure to unique pattern forming as a result of granular flow.*

Though this method does not explicitly allow calculation of the velocities of individual soil particles, it does allow estimation of a regularly spaced velocity field. While such visualization techniques have been widely employed in the field of experimental fluid mechanics, their application to the study of soils is a relatively new development.

3.5.3 Meso-scale model validation/registration

Model validation/registration at the meso-scale implies the ability to correlate the predicted and actual response of a controlled volume of regolith when subjected to an external load. This type of validation is valuable because it can yield insight into the failure mechanisms of granular materials. Meso-scale model validation is commonly pursued since the scale of interest makes testing methods practical. Two testing methodologies are commonly employed to characterize soil shearing response: direct shear test and triaxial shear test.

Direct shear testing is arguably the simplest and fastest way to measure critical terrain properties. In this test, soil is placed in a box composed of two halves that are able to slide relative to each other. A dead weight is applied to the top box in order to impose a state of homogeneous pressure (principal stress). Subsequently, one half of the box is held stationary while the other half is forced to slide at a controlled rate. Displacement and translational force are measured to produce shear vs. strain plots, and therefore estimate material shearing properties. With this methodology, a failure plane is forced to occur at a pre-determined location: the interface between the two box halves.

In triaxial shear tests of granular soils, the material is contained in a cylindrical latex sleeve with flat, circular metal plates capping the top and bottom ends. The main difference in triaxial tests (compared to direct shear) is that the stress applied in the vertical direction (along the axis of the cylindrical sample) can be different from the stresses applied in the horizontal directions perpendicular to the sides of the cylinder, (i.e. the confining pressure). However, standard triaxial tests are not true triaxial tests (where principal stress are different in all directions, $\sigma_1 \neq \sigma_2 \neq \sigma_3$) because confining pressure constrains two of the principal stress to be equal ($\sigma_1 \neq \sigma_2 = \sigma_3$).

From direct and triaxial test data, it is possible to extract fundamental material parameters about the sample, including its angle of shearing resistance, apparent cohesion, and dilatancy angle. These parameters can then be used in various types of computational models to predict material response in macro-scale engineering application. In principle, both testing methodologies should provide identical results. However, for direct shear tests, the boundary conditions are not fully controllable, leading to some discrepancies between the two methods.

Other non-standard meso-scale testing includes a variety of machine-soil interaction experiments that can be customized according to specific needs. For instance, a pressure-sinkage response for footings can be obtained by forcing a circular/rectangular plate perpendicularly into a mass of soil. This test is sometime referred as bevameter test, and is common in the terramechanics community. Another meso-scale test is represented by the moving wall test, in which a cutting blade is dragged through a body of soil at various angles of attack, while resistance forces are measured. In these tests it is possible to instrument the moving plates with pressure sensing elements (e.g. based on strain gauges, piezoelectric principle, etc.) able to estimate stresses at numerous discrete points along the plate-regolith interface. When coupled with kinematic data, such testing would allow for a richer characterization of soil loading and failure regimes than would be possible with either kinematic or pressure information alone.

3.5.4 Macro-scale model validation/registration

Model validation/registration at the macro-scale implies the ability to correlate the predicted and actual motion of an entire system of interest—a rover, spacecraft, subsurface penetrator, or other device—during interaction with a planetary surface or subsurface. Such validation is extremely important, because it provides confidence into high-level modeling tools that can be used during all phases of the mission life cycle. For example, validated rover mobility models can be used during the design phase to optimize rover suspension design, through the use of Monte Carlo simulation over a particular landing site. Validated models of spacecraft interaction with small bodies can be used during the tactical phase, to determine an optimized impact velocity and attitude.

Model validation at the macro scale is often performed by measuring the performance of instrumented spacecraft mockups or flight-space components operating in flight-analog conditions. An example of this would be validation of MER rover mobility performance models by comparing model predictions to measured performance of an MER test rover operating in the JPL Mars Yard. A key difficulty of such testing is the typical inability to replicate partial gravity, extreme temperatures, and high/low pressure conditions.

A significant current effort focused on macro-scale Mars rover mobility model validation is the ARTEMIS software package being developed by researchers at JPL, Washington University, and MIT [45]. This software is composed of a 200-element MSC-Adams dynamic rover model, a library of Bekker-Wong terramechanics subroutines, and high-resolution digital elevation maps of the Mars surface. Rover-terrain interactions that are modeled include longitudinal, lateral, and vertical wheel-terrain interaction forces, the effect of slip sinkage, and multipass effects. The model will be employed to help plan drives for Opportunity on Endeavour's rim, providing a set of outputs to help engineers choose routes to desired rock targets that minimize wheel sinkage and slip, and thus reduce the probability of embedding Opportunity (see Figure 22).

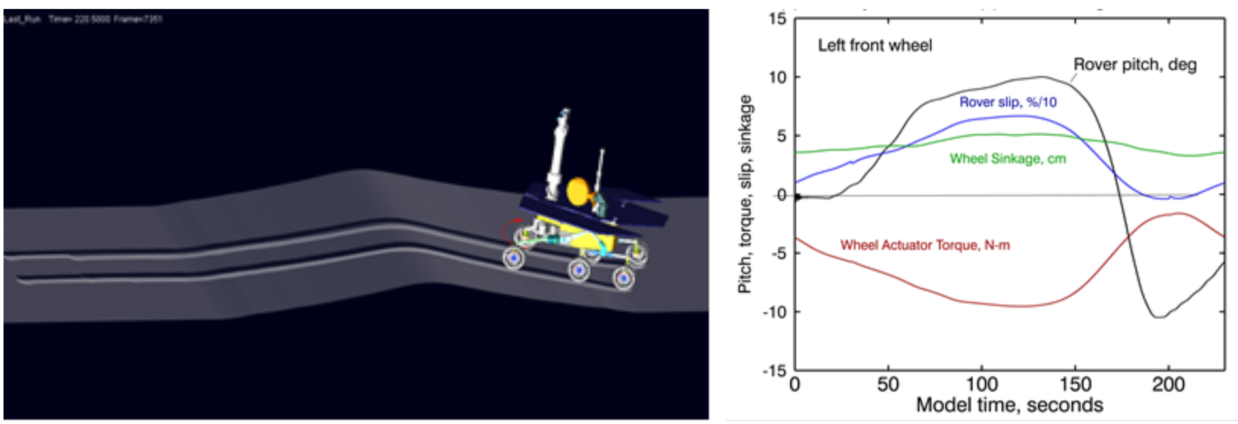


Figure 22: (Left) ARTEMIS MER rover model. Trailing tracks indicate roving in reverse. (Right) Plots of rover pitch. Positive values indicate that the front of the rover was pointing downhill relative to the local gravity vector. Note the increased left front wheel torques, sinkage, and slippage estimates as the rover ascended the ripple flank.

Validation of ARTEMIS is being pursued in several ways. The first is by validating simulated motion of an individual MER wheel against experimental data collected from an instrumented flight spare MER wheel traveling through MMR Mars regolith simulant in a soil bin at MIT (see Figure 23). In such tests, the wheel is driven under a controlled normal load, forward velocity, and slip ratio (a measure similar to the differential interface velocity). The wheel sinkage into the soil, net forward force, and required motor torque are then recorded. These measurements can then be compared to measurements produced by the ARTEMIS simulation for an identical scenario. In these simulations, regolith physical parameters employed in ARTEMIS are derived from experimental analysis of the MMR simulant.

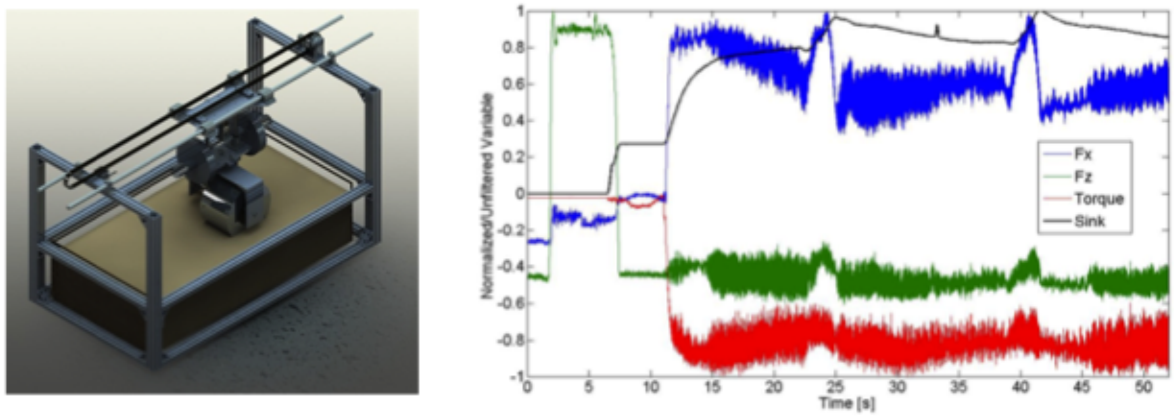


Figure 23: (Left) Dedicated spacecraft-regolith interaction test rig at MIT, shown fitted with MER-scale rigid wheel. (Right) Sample of measured quantities, including wheel displacements and torques.

The second validation method is by comparing modeled rover drive sequences to telemetry captured from the Spirit and Opportunity rovers during actual drive sequences. Here, the ARTEMIS simulation is provided with the identical drive command sequences that were provided to a MER rover on a specific sol. Then, the resulting motion trajectory of the rover is compared to telemetry. A key difficulty of this type of validation relates to soil parameter modeling in ARTEMIS, since the full suite of soil parameters required by the Bekker-Wong models is not available.

3.6 Applications to engineering systems for unknown celestial environments

xTerramechanics opens a new paradigm in space exploration, where "terrain is no obstacle." From a NASA project perspective, the goal is to develop a new architecture for Lifecycle Integrated Testing, Modeling, and Simulation (LITMS, Figure 24). The adoption of a structured systems approach to design, development, verification, and validation through LITMS will increase capabilities, lower risk, and reduce costs for planetary surface missions.

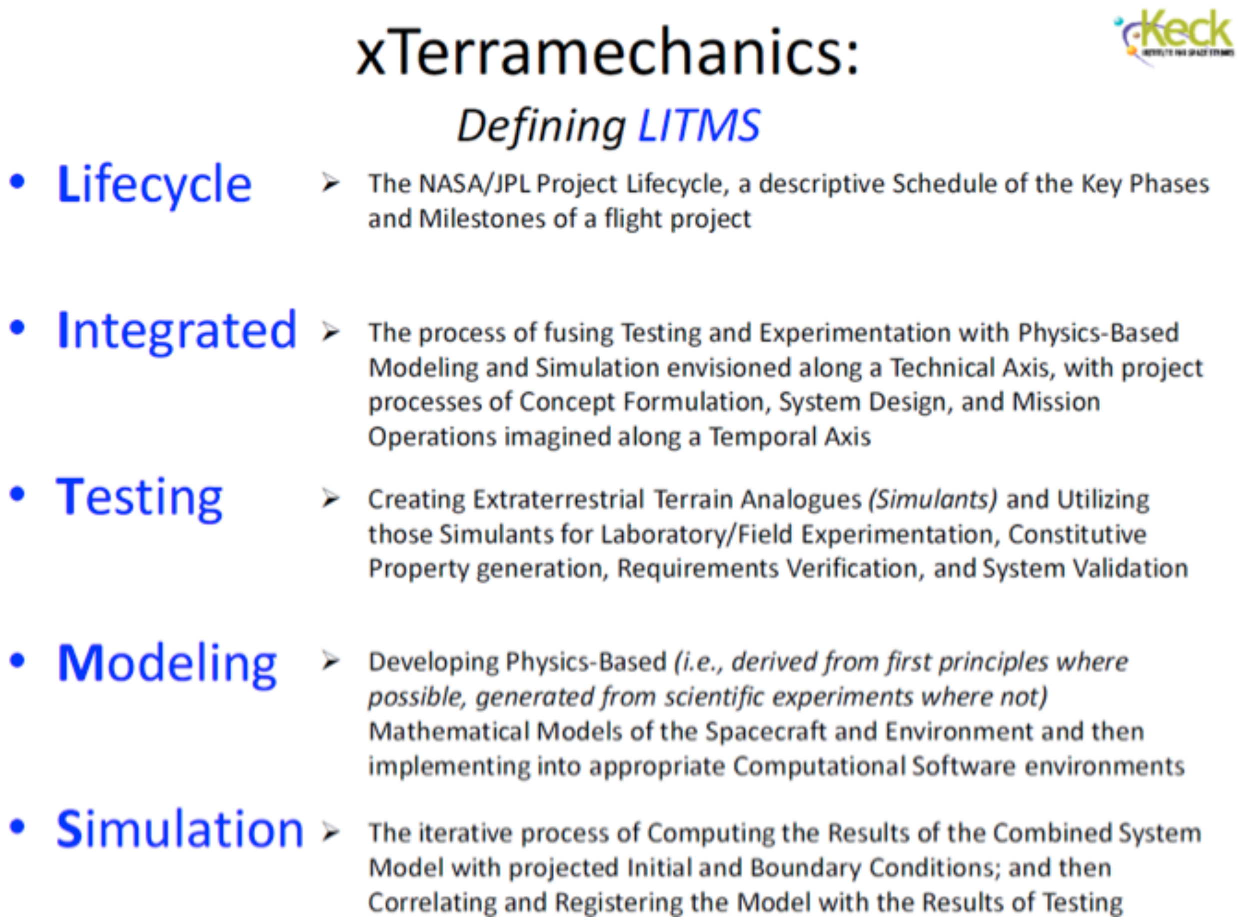


Figure 24: An Overview of a Mission Lifecycle-Centric Modeling Capability in xTerramechanics.

The approach described in the report is intended to enable revolutionary new mission concepts, perhaps some that are not currently on NASA's schedule. Such projects are on the precipice of sci-fi fantasy. More than being dreamy, the concepts illustrate the great need for xTerramechanics significantly beyond the current capabilites. Five examples of new mission concepts are presented in the following section. The concepts organically evolved from the workshop discussions – the artistic vision was drafted and presented by R. Lindemann (8/3/2011).

3.6.1 Radical mission concepts enabled by xTerramechanics life-cycle modeling

Looking for evidence of life on Europa

Figure 25 illustrates a Europa ice-cliff climbing robot looking for evidence of life frozen in the radiation-shielded areas of the moon's icebergs and crevasses. The potential mission might include a climb down a cliff wall that is permanently shadowed from the intense radiation flux of Jupiter and drill into the ice with sufficient depth to perform analytical chemistry experiments looking for organic compounds.

The conceptual robot is an articulated and segmented "inch worm" autonomous-repelling legged rover that statically anchors one section into the ice to stabilize itself while the tandem section extends the vehicle's reach, followed iteratively by the two sections reversing their roles.

A possible destination is a water-ice glacier thrust upward from Europa's frozen ocean. The science goal is for the robot to climb down the nearly walls of the ice cliffs in order to clear the radiation weathered zone which would quickly destroy the robots avionics and would have long ago destroyed any organic compounds that were frozen into the Ice before being uplifted.

Radical new paradigm: 'Terrain is no obstacle'

- *Descending of Europa ice-cliffs. Navigating the coated rocks nearby ethane-methane lakes of Titan. Drilling the surface of Io. Touch-and-go sampling on Venus.*
- *The envisioned futuristic concepts provide exciting new science mission platforms in which xTerramechanics could play an enabling role.*

Investigating the nature of methane-ethane lakes on Titan

A mission concept for an amphibious rover on Titan is shown in Figure 26. Such a mission would be to land on the surface of Titan with a versatile and robust aquatic roving vehicle capable of traveling over an extremely diverse terrain of rough natural terrains, performing a first of its kind of mission of exploration and scientific discovery. The environment consists of rocks and ices with rivers and lakes of liquid ethane and methane, in addition to winds and rain of mixed liquid hydrocarbons.

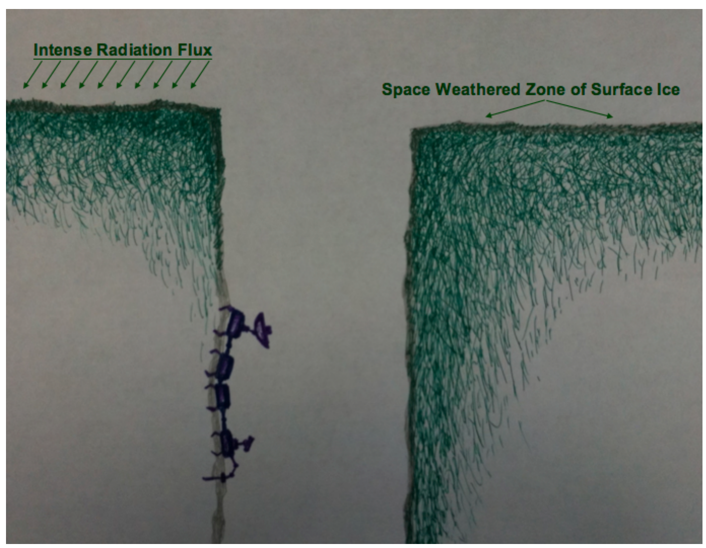


Figure 25: Mission concept: a climbing robot descending down Europa's steep icy cliff.

The imagined vehicle is a robotic walking rover and boat, which can autonomously swim, climb, and walk over the extremely unusual terrain while performing remote sensing, safe navigation, and sample acquisition and analysis. Potential science goals are to characterize the smog-filled atmosphere, map the surface mineralogy and terrain, and explore the hydrocarbon hydrology of the rivers and lakes, searching for complex organic compounds.

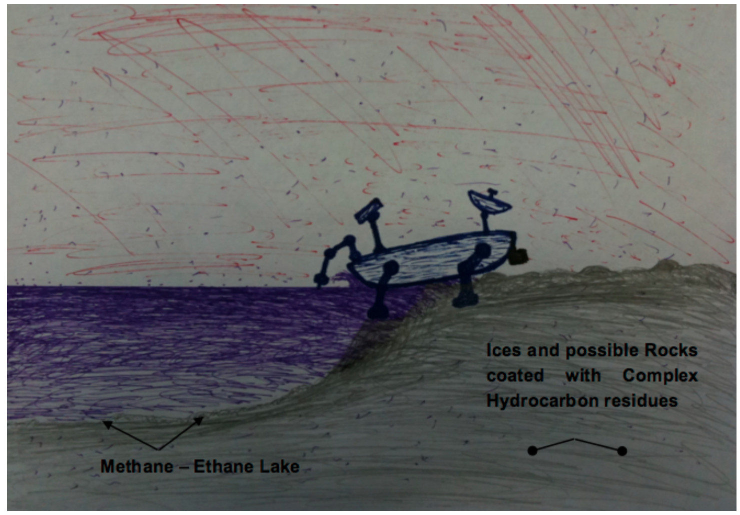


Figure 26: Mission concept: Titan amphibious rover exploring and sampling the ethane-methane lakes and shorelines of a cryogenic world.

Discovering the underground mineralogy on Jupiter's moon Io

Figure 27 envisions an Io drilling and sub-surface sampling explorer, capable of investigating the solar system's most volcanic environment. The mission would land on the surface of the highly volcanic and intensely radiated surface of Jupiter's moon Io, and rapidly perform a science mission by drilling meters into the surface to chemically sample the mineralogy, in addition to performing surface science experiments. The vehicle is a highly shielded spacecraft/lander with a robotic sampling arm, deep drilling sampler, and analytical chemistry instruments in addition to typical remote sensing instruments and cameras. By core sampling near the surface, the robot would extricate a scientific history of the layers of ash deposited by Io's volcanoes.

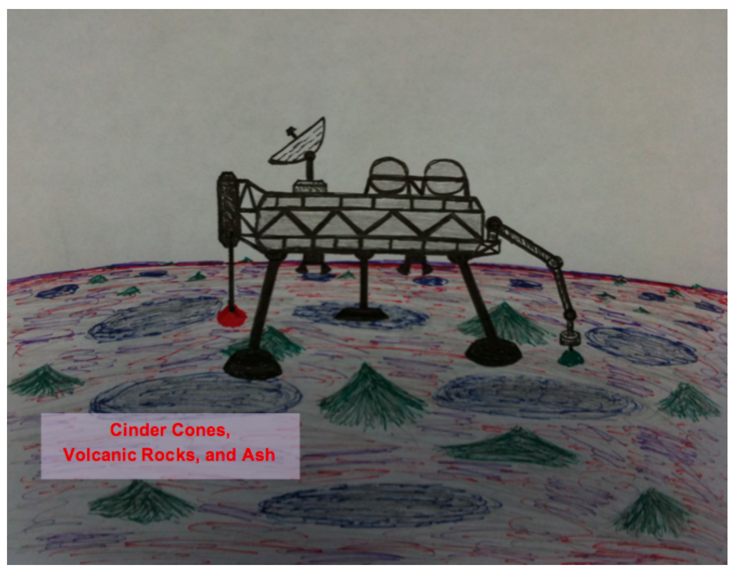


Figure 27: Mission concept: drilling and sub-surface sampling explorer on Io.

Navigating the inhospitable atmosphere and collecting surface samples on Venus

A Venus balloon with touch-and-go sampling is shown Figure 28. The challenge of such surface exploration is the fast sample acquisition and handling in the extreme surface environment of Venus. A mission would perform fast sampling missions before quickly ascending to protect the spacecraft balloon, perform scientific analysis, and then travel to a new site in the near Earth-like environment of the Venusian *upper* atmosphere.

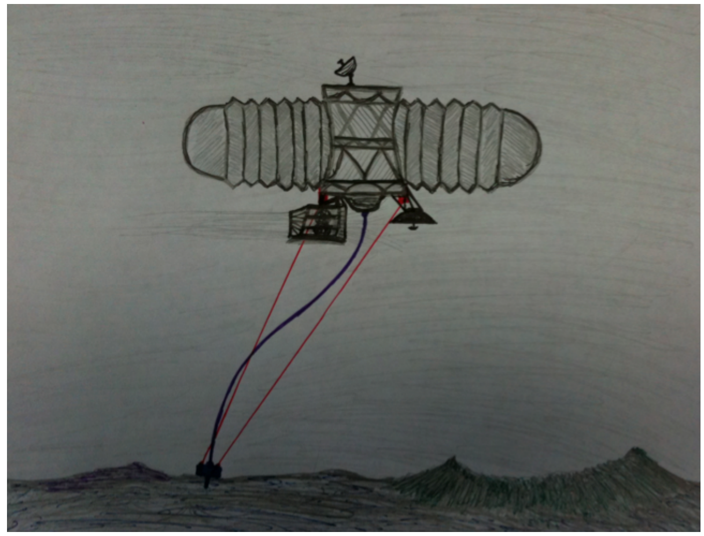


Figure 28: Mission concept: Venus balloon with touch-and-go sampling capabilities.

A potential vehicle is a highly expandable metallic balloon utilizing a phase changing liquid/gas material which allows the vehicle to descend from an Earth-like environment of 1 atm pressure and near 0 C to its 1400 psi supercritical CO_2 atmosphere and near 500 C surface. The mission could involve a speedy science sample acquisition, prior to re-ascent to the upper atmosphere for analysis, data transmissions back to Earth, and a continued voyage.

Investigating the geology of the steep hillsides and crater rims on Mars

Finally, Figure 29 envisions a Mars cliff-repelling rover exploring the steep hillsides and crater rims where evidence of seasonal sporadic water emissions has been observed from orbit. Such a mission would require a thorough understanding of at-depth terramechanics required to anchor the base at the top of the rim. The surface could be initially prepared via localized wheel trenching and subsequent anchor drilling performed using the science tools available on-board. Anchoring would allow the rover to progress downward and look for the presence of water at various cliff strata.

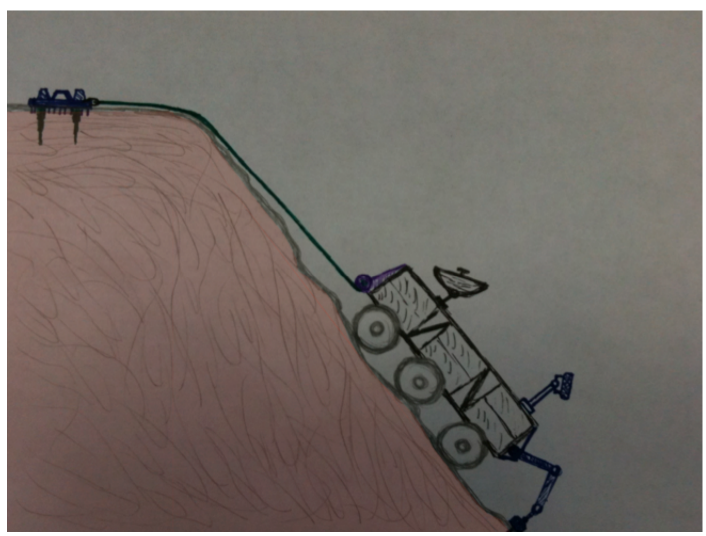


Figure 29: Mission concept: anchoring a cliff-rover on Mars to enable investigation at different wall strata.

3.6.2 NASA science mission directorate targets

NASA produces Roadmaps to describe the directions and strategic goals of its different mission directorates. The Science Mission Directorate of NASA further breaks down robotic exploration and science goals for the solar system into a number of different themes. Four of the science and exploration themes for our solar system include: “the Earth and Moon”, “Mars”, “Primitive Bodies” (i.e., asteroids and comets), and finally “Outer Planets” (i.e., the four Gas and Ice Giant planets plus their associated moons).

On many of these bodies that represent the very highest priority science mission targets, the regolith surfaces are known, via previous missions and remote sensing, to be substantially composed of granular media. Some specific targets include the Moon, Mars, Europa, Titan, and the asteroids and comets that have been closely observed. Two of these bodies, Mars and Titan, have substantial atmospheres and visible Aeolian features like sand dunes have been observed. The other target bodies mentioned have no atmosphere but other types of granular regolith mechanics have been observed including “Air-fall” deposits and the effects of avalanches. Therefore dealing with the system interaction of granular regolith and spacecraft is both important in the direct science investigation sense of understanding the history and present state of the surface environment, and also indirectly in terms of planning missions and operations around those interactions. An excellent example of both cases can be seen with planning and understanding the mobility performance of a wheeled rover on the Moon or Mars.

The overwhelming importance of this research thrust to NASA can be seen therefore in the broad application of this development activity to practically every in situ or surface mission to a planetary body that NASA would embark upon for the foreseeable future.

3.7 Other topics of interest

With experts from a variety of fields on hand to tackle diverse topics of discussions, it was inevitable that plethora of ideas would be generated. Some of the ideas that surfaced but were not explored in sufficient depth do the limited time and/or focus of discussion, are listed below:

Corporate Memory

During the workshop, the issue of corporate memory has been raised. For instance, some of the challenges that NASA designers faced for Sojourner, MER, and MSL missions were not extremely dissimilar from the Apollo era ones. However, the lack of continuity into NASA/JPL operations, forced the engineers and scientists to rethink solutions from ground up.

Bridging the fields

In the field of soil mechanics, an existing gap between the researchers in granular physicics and geomechanics was acknowledged. Similarly, a gap is present between the researchers studying geomechanics and terramechanics. Bringing the academic literature between these fields closer together, via active collaborations across the fields, was identified as a critical challenge the xTerramechanics community will need to face.

Uncertainty quantification

Uncertainty quantification remains a central topic for any innovative approach into spacecraft-regolith interactions at distant celestial bodies. To this end, it is necessary to have a robust, physics-based, deterministic model in place. The ability to quantify uncertainties *will* improve design, testing, and operation, thereby decreasing the mission cost and reliability.

Novel Lander Instrumentation

The mobility platforms (Sojourner, MER, and MSL) sent to Mars have covered many miles on the surface of the planet. The lack of advanced machine-terrain modeling capabilities, however, has limited the exploitation of mobility data for regolith parameter estimation. Specifically, back-analysis of rover telemetry collected over the past missions could provide a *localized surface geologic survey* of Mars at a scale different than that captured by remote sensing, e.g. satellites, and pave way for enhanced instrumentation (e.g. on-board radar) in the future landed missions.

Machine Design

A foreseeable outcome of xTerramechanics is the possibility to improve machine design. Improved knowledge of machine-regolith interaction can guide the design phase toward more effective solutions. Participants believe that this can be a design game changer because it would lead to significant reduction of parameter space needed in design, and pave way for discoveries of phenomena not considered during macroscopic tests.

Surface Engineering

In ambitious missions that include sample return, or in-situ regolith sampling, a new class of non-adhesive materials is needed. Drilling tools, conveyor structures, valves and other mechanical parts suffer from 'stickiness' of regolith. This doesn't just include regolith clumping, but also adhesion to tools, possibly compromising the repeat sampling. Active surface control would be a significant game changer for this class of problems.

Mobility

When talking about mobility, the canonical example of Spirit embedding incident comes to mind first. However, other mobility related mission aspects would significantly benefit from xTerramechanics. Real-time planning, tactical planning, and strategic planning are an evident example. On-line self-diagnostics and fault tolerance operation are tools that may become available in the near future.

Guidance

Existing measurements, e.g. visual odometry (on-board) or thermal inertia (remote orbit), provide an untapped tool that could assess terrain properties and provide engineering and scientific basis for in future path planning activities. At present, this task relies on limited human experience and limited history of landed missions.

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Appendix

A. Workshop Agendas

Workshop 1, 6/20 – 6/24, 2011

Monday, June 20, 2011

Short Course on Measurements and Models at the Surface of Mars
(Salvatori Seminar Room, South Mudd)

Time	Event	Speakers	Leaders	
8:30 - 9:00	Coffee and refreshments		B. Trease	I. Vlahinich
9:00 - 9:45	Current State of the Art in Surface Measurements for Martian Geology	Ray Arvidson, Wash. U.		
9:45 - 10:30	Mars Surface Analogues on Earth - Mechanical Properties of Regolith	Bob Anderson, JPL		
10:30 - 11:00	Break			
11:00 - 11:45	Current Methods for Surface Interaction Modeling - Soil Mechanics	José Andrade, Caltech		
11:45 - 12:30	Current Methods for Surface Interaction Modeling - Engineers	Karl Iagnemma, MIT		
12:30 - 2:00	Informal lunch for all attendees			

Workshop: xTerramechanics - Integrated Simulation of Planetary Surface Missions
(KISS Seminar Room 621, Millikan 6th Floor)

Time	Event	Speakers
2:00 - 2:30	KISS Logistics and Overview	Michele Judd / Tom Prince
2:30 - 3:00	Welcome and Introductions	José Andrade, Caltech
3:00 - 4:00	Distinguished Visiting Scholar Keynote -Big Picture of Terramechanics role in Planetary Science -Introduction of the Canonical "Rover" Problem	Raymond Arvidson, DVS
4:00 - 4:30	Break	
4:30 - 5:15	Mission Perspectives for xTerramechanics (MSL)	John Grotzinger, JPL
5:15 - 6:00	Motivations for xTerramechanics from the Planetary Decadal Survey	Gentry Lee, JPL
6:00 - 8:00	KISS Welcome Dinner at the Athenaeum (participants, dignitaries, managers, and department heads)	

Tuesday, June 21, 2011

The Basics

Time	Event	Speaker	Leaders	
8:30 - 9:00	Coffee and refreshments			
9:00 - 9:45	Overview of Soil Mechanics - Limitations and Future Directions	Amy Rechenmacher, USC	K. Iagnemma	D. Goldman
9:45 - 10:30	Fundamentals of Terramechanics - History and Limitations	Karl Iagnemma, MIT		
10:30 - 11:00	Break			
11:00 - 11:45	xTerra-materials - Characteristics of Regolith Composition	Bob Anderson, JPL		
11:45 - 12:30	Robots on Soil - Mechanical Issues Related to Terramechanics	Scott Moreland, CMU		
12:30-2:00	Buffet lunch at the Athenaeum provided by KISS			
2:00 - 2:30	Discussion and Brainstorming	ALL		
2:30 - 3:30	Break-out Sessions	ALL		
3:30 - 4:00	Break			
4:00 - 5:30	Poster Session	ALL		
6:00 - 8:00	Leave for offsite no-host dinner in Pasadena (but KISS will pay for grad students and postdocs who attend)			

Wednesday, June 22, 2011

The Methods			
Time	**Event**	**Speaker**	**Leaders**
8:30 - 9:00	Coffee and refreshments		
9:00 -9:45	FEA-based Techniques	Liqun Chi, Caterpillar	J. Andrade, N. Lapusta
9:45 - 10:30	DEM-based Techniques	Jerry Johnson, UAF	
10:30 - 11:00	Break		
11:00 - 11:45	Techniques in Granular Media Flow	Josette Bellan, JPL	
11:45 - 12:30	Integrated Methods - Multi-scale Modeling, Curve-fitting, Serial & Parallel Architectures	José Andrade, Caltech	
12:30 - 2:00	Lunch on your own		
2:00 - 3:00	Break-out Sessions	ALL	
3:00 - 3:30	Break & Campus Walk		
3:30 - 5:00	Discussion and Brainstorming at the Athenaeum	ALL	
6:00 - 8:00	Leave for offsite no-host dinner in Pasadena (but KISS will pay for grad students and postdocs who attend)		

Thursday, June 23, 2011

The Reality			
Time	**Event**	**Speaker**	**Leaders**
8:30 - 9:00	Coffee and refreshments		
9:00 -9:30	Broader Interests and Applications -Sample Handling -Mobility -Terra-forming	Randy Lindemann, JPL	R. Lindemann, R. Mukherjee
9:30 - 10:00	Architecture of Collaboration, Development, and Operation	Brian Trease, JPL	
10:00 - 10:30	Applications in Design	Dimi Apostolopoulos, CMU	
10:30 - 11:00	Break		
11:00 - 11:45	Model Verification and Validation	Lee Peterson, JPL	
11:45 - 12:30	Applications in Mission Operations	Ashley Stroupe, JPL	
12:30 - 2:00	Lunch on your own		
2:00 - 3:30	Discussion and Brainstorming	ALL	
3:30 - 4:00	Break		
4:00 - 6:00	Break-out Sessions	ALL	
6:00 - 8:00	KISS Dinner at the Athenaeum (everyone expected to attend, spouses encouraged to attend)		

Friday, June 24, 2011

Wrap Up		
Time	**Event**	**Speakers**
8:30 - 9:00	Coffee and refreshments	
9:00 - 10:15	Wrap-up Close-out Action Items	ALL Organizers - Mandatory Others - Optional
10:15 - 10:45	Break	
10:45 - 12:30	Future Planning Wiki Updates	ALL Organizers - Mandatory Others - Optional
12:30 - 2:00	Buffet lunch at the Athenaeum provided by KISS	

Study Period

- 7/11 Monday: 9AM-5PM (with breaks and lunch)
- 7/12 Tuesday: 9AM-lunch JPL Tour: MSL Scarecrow, Athlete, Moonrise
- 7/12 Tuesday: lunch-5PM (with breaks)
- 7/13 Wednesday: 9AM-5PM (with breaks and lunch)

Workshop 2, August 1-3, 2011

KISS xTerra Workshop #2

	Monday, Day 1	Tuesday, Day 2	Wednesday, Day 3
	All talks are 20-30 minutes		
8:30-9AM	COFFEE AND REFRESHMENTS		
9AM-12:15PM (with 30 minute break)	Talk 1: Welcome and Intros (several new participants) Talk 2: Recap/Summary of Workshop 1 and Study Period Talk 3: Goals for Workshop #2 -Outline of our 3-pronged modeling plan, with cross-functional interaction -3 canonical cases: Rover Mobility, Sample Transfer, Small-body Sample Acquisition	Talk 1: Full-field Granular Physics Approach •Followed by discussion Talk 2: Full multi-scale Physics Approach •Followed by discussion	Talk 1: Revolution, not evolution! -Present Randy's slide with 5 radical mission-enabling ideas Talk 2: John Peters, Army ERDC Future needs Activity: Small-group Brainstorming Brainstorm radically innovative out-of-the-box ideas.
12:15-1:45PM	LUNCH		
1:45-5:15PM (with 30 minute break)	Talk 4: J.Y. Wong, Terramechanics Open Discussion Role and Importance of Reduced-order modeling in the future of xTerramechanics Talk 5: Stein Sture, Luna-mechanics	Talk 3: Engineering Physics Approach •Followed by discussion Activity: For the previous 3 talks, debate and formally list: •Strengths, Applications •Challenges -What needs attention first? Most?	Concluding Discussion Activity: Small-group outlining of specific research programs What to work on first? Summarize Outcomes Future Program Manager Briefings
6PM	GROUP DINNER	GROUP DINNER	

B. Workshop Survey

Results for the xTerramechanics Workshops has not been compiled by KISS as of March 28, 2012.

C. Participants

Legend: o = present; x = absent

First Name	Last Name	FIRST WORK-SHOP	Study Period	SECOND WORK-SHOP	Institution	Discipline
John	Peters	x	x	o	Army ERDC	Simulation of Granular Media
José	Andrade	o	o	o	Caltech	Computational Mechanics / Geomaterials
Joel	Burdick	o	x	x	Caltech	Robotics
Melany	Hunt	o	o	o	Caltech	Soil Mechanics, Granular Physics
Michael	Lamb	o	x	o	Caltech	Geosciences, Granular Flow
Nadia	Lapusta	o	x	o	Caltech	Geosciences, Numerical Methods
Michael	Ortiz	x	x	o	Caltech	Computational Mechanics, Multiscale Analysis
Jo Y.	Wong	x	x	o	Carleton University	Fundamentals of Terramechanics
Dimi	Apostolopoulos	o	x	x	Carnegie Mellon	Robotics and vehicle-terrain mobility
David	Wettergreen	x	x	remote	Carnegie Mellon	Robotics and Autonomy
Liqun	Chi	o	x	x	Caterpillar Co.	Construction Automation, Machine/Ground Interaction
Sally	Shoop	x	x	o	CRREL	Terramechanics
Gill	Pratt	o	x	x	DAPRA	Defense Sciences Office
Dan	Goldman	o	x	x	Georgia Tech	Mobility in Granular Media
Robert	Anderson	o	x	o	JPL	Geophysics & Planetary Geosciences
Josette	Bellan	o	o	o	JPL	Physics-based Fluids Modeling
Paolo	Bellutta	o	o	o	JPL	Mars Rover Driver Operations

Don	Bickler	o	o	o	JPL	Planetary Rover Design
Randel	Lindemann	o	o	o	JPL	Spacecraft Engineering
Jaret	Matthews	o	x	x	JPL	Robotic systems engineering, extreme environment
Rudra	Mukherjee	o	o	x	JPL	Robotics Modeling, Simulation, and Visualization
Lee	Peterson	o	x	x	JPL	Simulation and Model Verification & Validation
Ashley	Stroupe	o	x	x	JPL	Mars Rover Driver Operations
Brian	Trease	o	o	o	JPL	Multi-body Dynamics
Brian	Wilcox	o	x	x	JPL	Robot System Technologies
Karl	Iagnemma	o	o	o	MIT	Robotics and Autonomy
Colin	Creager	o	x	o	NASA-GRC	Surface Mobility
Rob	Ambrose	o	x	x	NASA-JSC	Robotic Flight Systems
Jerome	Johnson	o	remote	o	U. of Alaska	Soils, Discrete Element Model.
Stein	Sture	x	x	o	UC Boulder	Lunar Regolith and Mobility
Amy	Rechenmacher	o	o	o	USC	Granular Media Experimentalist
Raymond	Arvidson	o	x	remote	Wash U, St. Louis	Planetary Science/Geochemistry

Post-doctoral Fellows and Graduate Students						
Ivan	Vlahinic	o	o	o	Caltech	Post-doc in Geo- and Computational Mechanics
Scott	Moreland	o	x	remote	Carnegie Mellon	Graduate Student in Terramechanics
Krzysztof	Skonieczny	o	x	o	Carnegie Mellon	Graduate Student in Terramechanics
Yang	Ding	o	x	x	Georgia Tech	Graduate Student in Granular Media Robotics
Carmine	Senatore	o	o	o	MIT	Post-doc in Terramechanics